In-Depth Survey Report

Comparison of the Performances of Three Acoustic Test Fixtures Using Impulse Peak Insertion Loss Measurements Rudyard Michigan

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Contents

Abstract

The purpose of this study was to evaluate three acoustic test fixtures (ATFs) using four hearing protector conditions and the methods in the ANSI/ASA S12.42-2010 standard. In 2009, the U.S. Environmental Protection Agency (EPA) proposed an impulse noise reduction rating (NRR) for characterizing the performances of hearing protection devices using the impulse peak insertion loss (IPIL) methods as outlined in the ANSI/ASA S12.42-2010 standard. The proposed EPA method measures the occluded and unoccluded response of an ATF in the presence of impulse noise at levels of 132, 150 and 168 decibels peak sound pressure level (dB peak SPL). The IPIL is the mean difference between the unoccluded and occluded responses measured in the fixture.

The performances of the high-fidelity (HiFi) Etymōtic Research ETYPlugs® earplug, the electronic level-limiting Etymōtic EB-1 BlastPLG™ earplug, the 3M™ Peltor™ TacticalPro Communications Headset earmuff and the dual protector combination of the ETYPlugs® earplug and the TacticalPro earmuff were evaluated on a single-ear and two dual-ear ATFs at the three impulse levels listed above. The French German Research Institute de Saint Louis (ISL) built both an unheated single-ear ATF (ISL-1) with 10 millimeter (mm) ear canals and a dual-ear heated ATF (ISL-2) with 12 mm ear canals. G.R.A.S. Sound & Vibration (GRAS) provided a heated dual-ear fixture (GRAS-45CB) with 18 mm ear canals. Five samples of each protector were fitted five times on each fixture or inserted in the ear canals of each fixture. For each fitting, three shots were measured. Impulses were generated using a Colt AR-15 0.223 caliber rifle.

ETYPlugs® earplug exhibited an increase in IPIL on each fixture as the impulse levels increased. Overall, for this earplug the ISL-2 fixture exhibited greater IPIL values compared to the dual-ear GRAS 45CB fixture while the ISL-1 fixture had the lowest IPIL values across all three impulse levels.

EB-1 BlastPLG™ earplug tested in the unity gain mode also displayed an increase in IPIL with increasing impulse levels for all three fixtures. The GRAS 45CB fixture displayed the highest IPIL values for this protector compared to the ISL-1 and ISL-2 fixtures. The two ISL fixtures exhibited similar IPIL results at the 132 and 150-dB impulse levels but at the 168-dB impulse level the ISL-2 fixture was approximately 7.0 dB greater.

TacticalPro™ earmuff also provided an increase in IPIL on all three fixtures with increasing impulse levels. For this earmuff, both of the ISL fixtures exhibited greater IPIL values compared to the GRAS 45CB fixture. The ISL-1 and ISL-2 fixtures had comparable IPIL at all three impulse levels.

For the dual protection condition, the IPIL also increased with increasing impulse levels. Overall, the single-ear and dual-ear ISL fixtures exhibited significantly greater IPIL compared to the GRAS 45CB fixture across all three impulse levels. The average IPIL differences observed between the ISL-1 fixture and the GRAS fixture were approximately 14.8 dB while the average IPIL difference observed between the ISL-2 fixture and the GRAS 45CB fixture were approximately 16.2 dB across all three impulse levels.

The mean IPILs increased with increasing impulse peak pressure on all three ATFs for all four hearing protection devices tested in this study. This research has demonstrated that the three fixtures evaluated using the ANSI/ASA S12.42-2010 method and four hearing protection conditions did not generate similar IPIL values and the differences varied as a function of hearing protector type and impulse level. In general for the two dual-ear fixtures, the earplug-only conditions generated comparable IPIL while for the single-ear fixture the earplug-only conditions produced lower IPILs. The earmuff only and the dual-protection conditions produced similar IPIL for the ISL-1 and ISL-2 fixtures but consistently generated lower IPIL for the dual-ear GRAS fixture. It is recommended the differences observed in the performances of the GRAS and ISL-2 fixtures with the earmuff and dual-protection conditions should be further investigated with the newer and improved version of the GRAS fixture. Furthermore, the ear canal of the ISL-2 fixture should be longer than 12 mm to permit testing earplugs that require more insertion depth such as formable plugs.

Introduction

The current U.S. Environmental Protection Agency (EPA) labeling regulation for hearing protectors states, “Although hearing protectors can be recommended for protection against the harmful effects of impulse noise, the Noise Reduction Rating (NRR) is based on the attenuation of continuous noise and may not be an accurate indicator of the protection attainable against impulse noise such as gunfire” (EPA, 1979). The NRR for a typical passive hearing protector seems to provide a lower bound for the attenuation of a protector when used in impulse noise (Murphy and Tubbs, 2007; Murphy et al., 2012; Khan et al., 2013). The upper bound of attenuation appears to be the bone conduction limit (Berger et al., 2003; Khan et al., 2013).

In 2009, the EPA proposed the use of a new metric for characterizing the performance of hearing protection devices in high-level impulse noise (EPA, 2009). The new method measures the difference between the unoccluded and occluded peak pressure levels or impulse peak insertion loss (IPIL) of a hearing protection device by evaluating multiple product samples with three ranges of peak impulse levels, and multiple fittings of the samples on an acoustic test fixture (ATF). The EPA did not specify the use of a particular ATF in their proposed rule. The EPA provided their proposed methodology to Working Group 11 of the American National Standards Institute Subcommittee 12 for Noise to standardize the measurement technique. The revised standard, ANSI/ASA S12.42-2010, which recommended testing the protectors at impulse levels around nominal values of 132, 150 and 168 decibels peak sound pressure level (dB peak SPL). These peak levels can vary within a range of ± 2 dB and the initial overpressure (A-duration) can vary between 0.5 and 2.0 milliseconds (ms).

The purpose of this study was to evaluate three different ATFs with four hearing protection conditions using the methods described in the ANSI/ASA S12.42-2010 standard. G.R.A.S. Sound & Vibration (GRAS) and the French German Research Institute de Saint Louis (ISL) both developed ATFs to comply with the new standard. NIOSH utilized an existing ISL-1 ATF and purchased the newly designed ISL-2 fixture in 2011. GRAS also provided a fixture to use in this comparison study. The new ISL-2 and the GRAS 45CB ATFs had longer usable ear canals and had simulated flesh in the ear canal and circumaural area surrounding the pinnae. The new fixtures were also heated so that ear canal flesh is kept near 37 °C. The third (original NIOSH) fixture was a single-eared fixture and was built by ISL in 2001 according to their original designs (Parmentier et al., 2000). The purpose of including the third fixture in this study was to compare the performance with previously published data collected with the original ISL fixture (Murphy and Tubbs 2007; Murphy et al., 2012).

Summarized in this report are the results of IPIL measurements for four hearing protector conditions on three different ATFs with rifle shot noise as the impulse source. This research was conducted as a part of a NIOSH funded research project and coordinated with the National Hearing Conservation Association task force on noise exposures from recreational firearms. The measurements were conducted outdoors at a hunting camp near the town of Rudyard in Michigan’s Upper Peninsula from May 12-15, 2011.

Methods

In this study, three different ATFs were evaluated using the single-eared ISL fixture (ISL-1), and two newly designed dual-eared fixtures (ISL-2 and GRAS). The performance of the fixtures was assessed by comparing IPIL measurements obtained on each ear of the fixture in accordance with ANSI/ASA S12.42-2010. IPIL measurements were obtained for four hearing protector conditions; an electronic earplug, a moderately attenuating passive earplug, an electronic earmuff, and a combination of the passive plug and the electronic earmuff using an impulse noise produced by rifle shots.

Study Design

This study was designed to compare the performance of three ATFs using four hearing protector conditions at three impulse levels. For the open and occluded ear conditions, the three fixtures and three free-field microphones were positioned at the 132-dB, 150-dB and the 168-dB locations. Five samples of each hearing protection device were placed on each fixture. Waveform data was simultaneously collected at all three impulse levels with one fixture located at the 168-dB level, while the second fixture was located at the 150-dB and the third fixture was located at the 132-dB level. Three impulses (rifle shots) were measured after each HPD was fit on the fixture. This procedure was repeated until all the samples had been fit five times and measured on each of the fixtures. After all five sets of protectors were tested on the fixtures positioned at one impulse level, then the fixtures were repositioned at one of the other two locations and the process was repeated until each fixture was tested at all three impulse levels. This study was conducted over a period of two days, with data collection of approximately 6 hours on the first day and approximately 9 hours on the second day during which nearly 1000 rifle shots were measured.

Acoustic Source

All of the measurements were conducted outdoors at a hunting camp. Acoustic impulses were generated using a Colt AR-15 semi-automatic rifle firing a 5.56 mm (0.223 caliber) ORM-D Federal Ammunition cartridge with 55-grain full metal jacket bullet. The rifle was mounted on a rifle stand and it was operated by a single person using a lanyard attached to the trigger of the rifle. The shooter was positioned behind and to the left of the rifle stand. This arrangement minimized the acoustic reflections from the shooter and reduced acoustic shadows caused by the body if the shooter was positioned in the path between the source and the ATFs. All of the shots were fired into a berm of sand approximately 80 feet in front of the rifle. The field microphones and ATFs were on the right side of the weapon. The National Instruments data acquisition system, the computer and the computer operator were located inside a tent, approximately 14 meters behind and on the left side of the rifle and behind all ATFs.

Field Microphones

Three free-field microphones were used to measure the acoustic impulses generated by the rifle shots at three different locations behind and to the right of the rifle[1]. A

[1] 170 dB: 1.0m = 1.0x + 0.0 y; 150 dB: 3.5 m = 2.2x – 2.5y; 130 dB: 14.5m = 1.4x – 14.4y

Brüel & Kjær (B&K) 4136 quarter-inch pressure microphone was used for measuring the 132-dB acoustic impulses while a GRAS 40BD quarter-inch pressure microphone was used for measuring the 150-dB acoustic impulses. The 168-dB impulses were measured by a B&K 4138 eighth-inch pressure microphone. All three of the free-field microphones were oriented in grazing incidence and pointed upwards. The height of the microphones above the ground was the same height as the ear canals of the fixtures at 1.35 m.

Calibrations of the microphones were performed each day before the data were collected. A GRAS 42AP pistonphone was used to calibrate the fixtures and the microphones with a 250 Hz, 114-dB tone. The 42AP provided barometric corrections for the calibration levels.

The calibration tone was measured using the NIOSH Sound Power VI data acquisition software. From the root mean square (RMS) voltage and sound pressure, the sensitivity of each microphone was determined and stored in the measurement configuration file. The sensitivity was determined several times to ensure its stability. Each microphone's electrical signal, measured in volts, was multiplied by the sensitivity for the respective channel and then stored to disk in Pascals (N/m^2). Temperature and humidity were sampled at various times during data collection and recorded in the experiment logbook. Atmospheric absorption of the propagating impulse was less than about a tenth of a decibel over the distances tested in this study (Harris, 1966).

Acoustic Test Fixtures

The three ATFs evaluated in this study were the GRAS 45CB fixture with two ears, an ISL fixture with two ears, and an ISL fixture with one ear. The three fixtures were chosen to compare results with previously published data collected with the ISL fixtures (Murphy and Tubbs, 2007; Berger and Hamery, 2008; Murphy et al., 2012). The single-ear ISL ATF had an IEC 60711 ear simulator (B&K 4157 with a B&K 4398 quarter-inch microphone) with ear canal length of 10 mm and an inner diameter of 7.5 mm (Buck and DeMezzo, 2008).

For the ISL-2 ATF, the ear canals, pinnae, and area surrounding the pinnae were flexible and had a Shore OO durometer rating of 75 to 76 when at room temperature or when heated to body temperature of 37 °C. The ISL-2 ATF was equipped with a GRAS IEC 60711 RA0045-S5 ear coupler. Each ear simulator was equipped with a GRAS Type 40BP quarter-inch pressure microphone and GRAS Type 26AC microphone preamplifier and was powered by a GRAS Type 12AA power module. The ISL-2 had 12 mm ear canals with an inner diameter of 7.5 mm. (Buck et al., 2011).

The dual-ear GRAS ATF had ear canals with a length of 18 mm and diameter of 7.5 mm. The ear canals, pinnae, and area surrounding the pinnae had a Shore OO durometer rating of 55 when at room temperature or when heated to body temperature of 37 °C. The GRAS ATF was equipped with GRAS RA0045-S7 ear simulators that were a modification of the IEC 60318-4 ear simulator. Each ear simulator was equipped with a GRAS Type 40BP quarter-inch pressure microphone and GRAS Type 26AC microphone preamplifier and was powered by a GRAS Type 12AA power module.

Data Acquisition System

The data acquisition system was a National Instruments PXIe-1082 chassis, equipped with NI PXIe-4462 four channel boards that could acquire signals at a sampling rate of 204.8 kHz, 24-bit resolution, ±42 volts input range. The signals measured were sampled at 200 kHz. NIOSH Sound Power VI program controlled the data acquisition system. Signals were recorded and stored into MATLAB binary formatted .mat files for post processing.

The ATF and field microphones were simultaneously sampled and a pre-trigger interval of 0.1 seconds was used to collect 1.0 second samples. The impulse from the 168-dB microphone was the trigger. All eight channels of the NI PXIe-4462 boards were used to sample the fixture and the field microphones. Channel 0 of board 1 was connected to the free-field B&K 4138 microphone which measured the 168-dB impulses. Channel 1 of board 1 was connected to the GRAS 40BD ICP pre-polarized pressure microphone which measured the 150-dB impulses. Channel 2 of board 1 was connected to the free-field B&K 4136 microphone which measured the 132-dB impulses. Channel 3 of board 1 was connected to the microphone of the left ear of the dual-ear GRAS ATF. Channel 0 of board 2 was connected to the microphone of the right ear of the dual-ear GRAS ATF. Channel 1 of board 2 was connected to the microphone of the right ear of the single-ear ISL ATF. Channel 2 of board 2 was connected to the microphone of the left ear of the dual-ear ISL ATF. Channel 3 of board 2 was connected to the microphone of the right ear of the dual-ear ISL ATF.

Fixture Locations and Source Levels

A shooting lane was laid out and three measurement locations were identified to yield nominal peak sound pressure levels at the field probes of 132, 150, and 168-dB peak SPL. The ATFs and the field microphones were positioned with a direct acoustic path to the source and at the same distance from the source. All three fixtures were facing the impulse source such that the ear canal microphones were in grazing incidence.

The ear canals of the ATFs were tested at a height of 1.35 m above the ground in both the occluded and unoccluded conditions using the impulses generated at 132.6±1.0 dB peak SPL, 149.8±0.4 dB peak SPL, and 169.8±0.5 dB peak SPL. The A-duration varied in between 0.24 to 0.45 ms at 168-dB, 0.24 to 0.58 ms at 150-dB and 0.11 to 0.98 ms at 132-dB. The distances from the muzzle of the rifle to the ears of the fixtures were 1.0 meters for 168-dB, 3.5 meters for 150-dB and 14.5 meters for 132-dB levels.

The free-field microphones were kept fixed in the same locations throughout the study. However, the three acoustic test fixtures were systematically rotated through the three locations so that each fixture and set of hearing protectors was appropriately tested at each of the three impulse levels.

Atmospheric Conditions

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 13, 14, 2011), the average wind speeds measured at the Chippewa County International Airport were 8.6 ± 3.8 and 10.6 ± 2.9 miles per hour during the data collection periods respectively. The maximum wind gust speed recorded at the Chippewa Falls International Airport was 19.6 mph. The airport's property was adjoining to the hunting camp. The measurement site was shielded somewhat by the surrounding forest.

The temperature during the course of the measurements varied between 50 and 68 degrees Fahrenheit. The atmospheric pressure was 29.7 and 29.9 inches of mercury. The measurements of with the open microphones were minimally affected by the wind because the impulse levels were considerably in excess of any wind-induced artifacts.

Hearing Protection Devices

The performances of the Etymōtic Research ETYPlugs® earplug (ETYPlugs), the Etymōtic EB-1 BlastPLG™ earplug (EB1 BlastPLG) and the 3M™ Peltor™ TacticalPro™ Communications Headset earmuff (TacticalPro) were evaluated in this study. The ETYPlugs earplug and TacticalPro earmuff were also tested in a dual-protection combination. These protectors are illustrated in Figure 1. These protectors were selected to compare the attenuation results with an earlier study that was conducted with different acoustic noise sources (Murphy et al., 2012). The ETYPlugs are now manufactured with two different sized ear tips. The larger, white, flanged ear tips were tested rather than the smaller ear tips that have blue flanges.

Five samples of each protector were tested. The individual samples were numbered and earplugs marked to ensure that the same protectors were inserted into both the right and left ears of the fixtures. The ETYPlugs earplug provides a moderate level of attenuation and has an NRR of 16 dB. The EB1 BlastPLG has an NRR of 25 dB and has an electronic level-limiting amplification circuit that prevents it from amplifying sounds above 85 dB SPL. The EB1 BlastPLG has two settings that provide approximately 0 dB and 15 dB gain, which can be selected with a toggle switch (Killion, 2011). The lower, 0-dB gain setting was chosen for all of the tests. The TacticalPro earmuff is an electronic earmuff with an NRR of 26 dB. The earmuffs were mounted with the external microphones facing forward. The TacticalPro earmuff was tested with its electronics set to unity gain, which provides a nominal amount of amplification to be equivalent to the unoccluded condition. For HPDs that have a continuous variable gain setting, the ANSI/ASA S12.42-2010 standard recommends that unity gain be determined in a sound field with an ATF such that the unoccluded levels are approximately equal to the occluded levels. The combination of ETYPlugs earplug and TacticalPro earmuff used in this study is consistent with the NIOSH dual protection recommendation and it was expected to realize an IPIL uncorrected above 40 dB (NIOSH, 2009).

Data Analysis

The ANSI/ASA S12.42-2010 impulse signal analysis was implemented in MATLAB and is described below.

The beginning of the impulse analysis time window was 5.0 ms before the peak and the duration of the analysis window was 305 ms. For each impulse level, for each measurement repetition, and for each physical arrangement of the impulse source, free-field (FF) microphone(s), and acoustic test fixture (ATF) microphones, a unique transfer function, $H_{\text{ATF-FF},L,n}$(f), exists

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

where $P_{\mathrm{FF},L,n}$(f) and $P_{\mathrm{ATF},L,n}$(f) are the discrete Fourier transforms of the free-field and ATF impulse waveforms, at a given level *L* and repetition number *n*. For each test level, an average transfer function can be determined by dividing the Fourier transforms of the fixture and free-field impulses and averaging the result in the frequency domain across *N* unoccluded repetitions:

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

This averaged transfer function is used to estimate the unoccluded fixture response for an occluded trial, from the impulse measured at the field microphone,

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

where $P'_{\mathrm{ATF},L,i}(t)$ denotes the estimated unoccluded ATF pressure waveform, $P_{\mathrm{ATF},L,i}$(f) is the discrete Fourier transform of the free-field waveform for the same trial, and FFT^{-1} is the inverse discrete Fourier transform.

The IPIL is determined as the difference between the maximum absolute unoccluded and occluded peak sound pressure levels for the fixture, where *L* is the nominal peak level (132, 150, 168), *i* is the sample number, and *j* is the fitting number,

$$\mathrm{IPIL}(L,i,j) = 20\log_{10}\left(\frac{\max_t \left|P'_{\mathrm{ATF},L,i,j}(t)\right|}{\max_t \left|P_{\mathrm{ATF},L,i,j}(t)\right|}\right). \tag{4}$$

The IPIL(*L*, *i, j*) are averaged first over fittings to obtain an average IPIL for each sample and then averaged over samples to yield an average IPIL for each hearing protector device to generate the results shown in Tables 1-4.

Statistical Analysis

A repeated measures linear mixed model was used to analyze the data. The statistical model was run using the SAS *Proc Mixed* and Stata's *mixed* command (SAS, 2011; StataCorp, 2013). The data were collected systematically – meaning that measurements were made at a given nominal sound level for all types of HPD's for all samples for all repetitions before changing to the next nominal sound level. Similarly, measurements were made with a given HPD for all samples and repetitions before changing to the next HPD. Due to the large number of measurements it was not possible to randomize the order of sound levels or type of HPD. The analysis assumes that there is no effect due to the order in which sound levels and types of hearing protectors were presented. We believe that this assumption is reasonable because neither fatigue nor learning would be a factor for ATF's. The experimental unit for the analysis is a "sample", which refers to a specific, numbered hearing protection device (HPD). Each type of HPD had five samples. Each sample received 15 exposures to all of the nine possible combinations of fixture (ISL-1, ISL-2, and

GRAS) and impulse level (132 dB, 150 dB, and 168 dB). The analysis includes impulse level in the model as the nominal impulse level (as a categorical variable referring to impulse level). With this approach the least squares means from the model are the same as the arithmetic means of the data (with the exception of the excluded data from the faulty EB-1 protector). The model treats the data from the ISL-1 fixture as coming from the right ear. Finally, the variance of the residual is modeled as heterogeneous with respect to fixture, HPD, and impulse level. The statistical model was,

$$\begin{aligned} y_{ijklm} = \quad & \mu \quad + \alpha_i + \beta_j + \gamma_k + \delta_l + (\alpha\gamma)_{ik} + (\alpha\delta)_{il} \\ + \quad & (\beta\gamma)_{jk} + (\beta\delta)_{jl} + (\gamma\delta)_{kl} + (\beta\gamma\delta)_{jkl} + \epsilon_{ijklmn}. \end{aligned} \tag{5}$$

where

y_{ijklmn} = IPIL for ear i, fixture j, nominal sound level k, HPD l, sample m, and repetition n, n = 1,...,15 (3 shots for each of 5 fittings);

μ = overall mean;

α_i = fixed effect of ear i (left or right), i = 1, 2;

β_j = fixed effect of fixture j (ISL-1, ISL-2, or GRAS), j = 1, 2, 3;

γ_k = fixed effect of nominal impulse level k (132 dB, 150 dB, and 168 dB), k = 1, 2, 3;

δ_l = fixed effect of hearing protector l (EB1 BlstPLG,ETYPLugs,TacticalPro; and DualETYPlugsTactPro), l = 1, 2, 3, 4;

$(\alpha\gamma)_{ik}$ = interaction of fixed effects of ear and nominal impulse level;

$(\alpha\delta)_{il}$ = interaction of fixed effects of ear and protector;

$(\beta\gamma)_{jk}$ = interaction of fixed effects of fixture and nominal impulse level;

$(\beta\delta)_{jl}$ = interaction of fixed effects of fixture and protector;

$(\gamma\delta)_{kl}$ = interaction of fixed effects of nominal impulse level and hearing protector;

$(\beta\gamma\delta)_{jkl}$ = interaction of fixed effects of fixture, nominal impulse level, and hearing protector;

ε_{ijklmn} = error term for ear i, fixture j, nominal sound level k, HPD l, sample m, and repetition n. n = 1,...,15 (3 shots for each of 5 fittings) for which variance(ε_{ijklmn}) = σ^2_{jkl}, i.e., the variance is heterogeneous for different levels of fixture, HPD, and impulse level.

Results

Unoccluded Waveforms

Example waveforms from the free-field microphones and open ear conditions for all fixtures for this study are illustrated in Figure 2. The peaks of the free-field microphones for all three levels were set to occur at 1 ms to facilitate comparison.

The unoccluded peak levels for the three fixtures for the 168-dB impulses, varied from 178 to 179 dB, approximately 9 to 10 dB greater than the free-field peak levels. For continuous noise, the 3% distortion is 174 dB for the microphones that were used in the ear couplers of the GRAS and ISL fixtures. These limits are established for continuous noise and represent the RMS pressure. The unoccluded peak pressures were about 1.8 times the RMS pressure 3% distortion pressure. The waveforms associated with the three fixtures displayed similar trends, with the unoccluded peak levels of the three fixtures agreeing within 1 dB. The ground reflections for all three fixtures exhibited similar peak levels and occurred around 5.55 ms after the initial impulse. Overall, the acoustic impulses generated by the Colt AR-15 rifle at the 168-dB levels contained less reverberant impulse compared to the 132-dB and 150-dB levels.

For the 150-dB impulses, the unoccluded peak levels for the fixtures ranged from 155 to 157 dB, approximately 5 to 7 dB greater than the free-field levels. The waveforms associated with the three fixtures exhibited similar trends. The ground reflections appeared around 2.85 ms after the initial impulse. The overall peak levels for the three fixtures agreed within 1.4 dB. The waveforms associated with the three fixtures displayed similar levels of reverberant noises.

The unoccluded peak levels for the three fixtures ranged from 141 to 142 dB for the 132-dB impulse level, approximately 10 to 11 dB greater than the free-field levels. All three waveforms displayed similar peak levels across all three fixtures with the ground reflections occurring around 0.73 ms after the initial impulse. The peak levels measured on the three fixtures agreed within 0.7 dB. The waveforms associated with the GRAS fixtures displayed slightly less reverberant noise compared to the ISL fixtures.

Occluded Waveforms

An example of a 132-dB occluded impulse waveform for the four hearing protection conditions is illustrated in Figure 3. For the ETYPlugs earplugs, the waveform of the GRAS fixture exhibited the largest initial peak value while the waveforms of the ISL fixtures displayed larger secondary peak values. The EB1 earplug waveforms initially reduced the peak levels and then released the compression, which restored the unity gain of the reverberant impulse levels. For the TacticalPro earmuffs and the dual protector condition, the GRAS fixture exhibited significant low frequency oscillations that were less pronounced in the ISL fixtures. Overall, the ISL fixtures measured larger attenuations than the GRAS fixture for this earplug. The waveforms associated with the earmuff indicate the presence of low frequency components with the GRAS fixture, not with the two ISL fixtures. The waveform trends observed with the double-protection were similar to the earmuff only condition.

Occluded waveform examples for the 150-dB impulses are illustrated in Figure 4. The waveforms produced by the ETYPlugs earplugs for the three fixtures were similar, with the ISL-1 fixture exhibiting slightly larger initial peak levels compared to the other two fixtures. The waveforms associated with the EB1 earplugs produced similar peak levels for the two dual-ear fixtures but displayed larger secondary peak levels for the single-ear fixture. The TacticalPro earmuff displayed different responses for all three fixtures. The waveforms associated with the dual-ear GRAS fixture contained predominantly low frequency components while the waveforms associated with the ISL fixtures contained more high frequency components. The double-protection condition also displayed different attenuations across all three fixtures with the dual-ear GRAS fixture exhibiting the largest peak levels while the dual-ear ISL fixture displayed the smallest peak levels.

Occluded waveforms for the 168-dB impulses are illustrated in Figure 5. The ETYPlugs earplugs generated uniform attenuation across all three fixtures, with the

ISL-1 fixture producing the largest peak levels, followed by the dual-ear GRAS fixture and then the ISL-2 fixture. The EB1 earplugs produced the highest peak levels with the ISL-1 fixture and the lowest attenuation with the dual-ear GRAS fixture. The waveforms associated with the TacticalPro earmuff displayed high frequency components across all three ATFs. The waveforms associated with the two ISL fixtures contained greater levels of the high frequency components compared to the GRAS fixture. The waveforms associated with the double-protection condition for the three fixtures contained predominantly low frequency components. The GRAS fixture associated with the double-protection condition displayed the largest attenuation in comparison to the two ISL fixtures.

A-durations

A-durations for the impulses generated from rifle shots were measured with the three free-field microphones and are illustrated in Figure 6. According to the ANSI/ASA S12.42-2010 standard, the initial A-duration can vary between 0.5 and 2.0 ms. At the 168-dB impulse level, all of the A-durations were less than 0.5 ms. For the 150-dB impulses, approximately 10 percent of the A-durations were greater than 0.5 ms. At the 132-dB impulses, the A-duration data illustrates approximately 50 percent of the impulses were greater than 0.5 ms. The short A-duration data suggests that high frequency components dominated the rifle shots in the free field (Murphy et al. 2014).

Hearing Protection Devices

In this subsection and the ones that follow, the results of the IPIL measurements for the four hearing protection conditions using three ATFs are presented. The free-field peak levels are an average of the peak levels for the impulses measured with that HPD sample during its five fittings and three shots per fitting. The performance of each protector was evaluated on the three ATFs and at three impulse levels to determine if there were any statistically significant differences by fixture type and impulse level. The results of the average IPIL measurements for each sample as it was assessed for each ATF are summarized in Tables 1-4, the statistical analysis of the data are summarized in Tables 6-10 and the results are illustrated in Figures 7-10.

Etymōtic Research ETYPlugs® earplug

The ETYPlugs earplugs IPIL data are summarized in Tables 1 and illustrated in Figure 7. Generally, this earplug exhibited an increase in IPIL with the increase in impulse levels for all three fixtures. Overall, the ISL-2 fixture exhibited the highest IPILs at 150 and 168-dB impulse level while the ISL-1 fixture exhibited the lowest IPIL values for all impulse levels. The IPIL differences between the left and right ears of the GRAS fixture were not statistically significant for the 132 and 168-dB impulse levels. The IPIL values from the left and right ears of the ISL-2 fixture were not statistically significant at the 150 and 168-dB impulse levels.

The least square means for the IPIL differences between the right ear of the single-ear ISL and right ear of the GRAS 45CB fixtures were statistically significant at all three impulse levels (Table 6). The right ears of the ISL-1 and the right ear of the ISL-2 fixtures displayed IPIL differences that were statistically significant at all three impulse levels. The IPIL differences observed between the left ear of the ISL-2 with the left ear of the GRAS fixtures were statistically significant at the 150 and 168-dB impulse levels. The IPIL differences for the right ear of the ISL-2 with the right ear of the GRAS fixtures were statistically significant only at the 132 and 168-dB impulse levels.

Etymōtic EB-1 BlastPLG™ earplug

The EB-1 BlastPLG earplugs IPIL data are summarized in Table 2 and illustrated in Figure 8. Overall, this earplug displayed an increase in IPIL for all three fixtures as the impulse level increased. The sample number 5 in Table 2 associated with the left ear of the dual-ear ISL ATF at the 132-dB impulse level for this earplug was excluded from the study analysis due to the malfunction of the protector. The protector failed to provide amplification during the tests conducted at 132 dB. The battery could have been depleted, incompletely inserted or the unit could have failed. This failure was detected only during the post hoc data analysis and thus excluded.[2] Generally, the GRAS 45CB displayed greater IPIL values for this protector compared to the two ISL fixtures.

In Table 5, the IPILs measured from the right ear of the GRAS fixture were between 1.4 and 2.9 dB greater than the left ear. Similarly the right ear of the ISL-2 yielded IPILs between 0.9 and 3.1 dB greater than the left ear of the ISL-2 fixture. For both the GRAS and ISL-2 fixtures, the differences were statistically significant except the ISL-2 at 132-dB impulse level.

In Table 7, comparisons of the least square means of the IPILs between the same ears on the three fixtures all proved to be statistically significant for the EB-1 earplug. In most cases, the GRAS fixture exhibited the higher IPIL value. The least square means for the IPILs from the ISL-2 right ear were greater than the least square means at 150 and 168 dB impulse levels, but not so at the 132-dB impulse level where the difference was 1.9 dB.

3M™ Peltor™ TacticalPro™ Communications Headset earmuff

The TacticalPro earmuff IPIL data are summarized in Table 3 and illustrated in Figure 9. Overall, this earmuff exhibited an increase in IPIL on all three fixtures with increasing impulse levels. Both of the ISL fixtures exhibited greater IPIL values using this earmuff compared to the GRAS fixture. The ISL-1 fixture had slightly greater IPIL compared to the ISL-2 fixture at the 132 and 168-dB impulse levels. However, the maximum IPIL values across all three fixtures were about the same.

In Table 5, the least square means for the IPIL differences between the left and right ears of the two dual-ear fixtures are presented. At the 132-dB impulse level, the left ear IPIL values tended to be greater from the left ear than the right ear. However at the 150 and 168-dB impulse levels, the right ear tended to be greater than the left ear. The GRAS fixture exhibited statistically significant differences at the 132-dB impulse level and the ISL-2 exhibited statistically significant differences at the 168-dB impulse level.

In Table 8, the least squares means for the IPIL differences between the right ear of the GRAS and the right ear of the ISL-2 fixtures were statistically significant at all three impulse levels. The IPIL differences between the left ear of the ISL-2 and left ear of the GRAS fixtures were statistically significant at 150-dB and 168-dB impulse levels. The right ear of the ISL-1 ATF and the right ear of the GRAS ATF were

[2] The low/high gain switch was later replaced on the EB-1 sample 5 earplug.

statistically significant also at all three impulse levels. The right ears of the ISL-1 and ISL-2 ATFs exhibited statistically significant differences only at the 132-dB impulse levels.

Dual combination of ETYPlugs earplug and Tactical Pro earmuff

The dual protection ETYPlugs earplug placed in combination with the TacticalPro earmuff IPIL data are reported in Tables 4 and 10 and illustrated in Figure 10. The IPIL for dual-protection increased with increased impulse levels. From Table 4, the measured dual protection attenuations on the GRAS fixture were 28.3, 31.5 and 39.6 dB at the 132, 150 and 168-dB impulse levels. The measured dual protection attenuations on the dual-ear ISL-2 fixture were 37.3, 52.5 and 58.3 dB at the three impulse levels. For the single-ear ISL-1 fixture, the measured attenuations were 41.4, 46.5 and 54.2 dB at the three impulse levels.

From Table 5, the comparisons of the least squares mean IPIL differences from the right and left ears of the GRAS fixture were significant at the 132 and 150-dB impulse levels. At the 132-dB impulse level, the left ear IPIL was greater than the right ear IPIL by 3.6 while at the 150-dB impulse level the right ear IPIL was greater than the left ear IPIL by 2.1 dB. For the ISL-2 fixture, the least squares mean difference was statistically significant at the 132-dB impulse level.

In Table 9, the differences between fixtures are compared. For all fixtures and impulse levels, the differences were statistically significant.

In Table 10, the summary IPIL values for the single protection and the dual protection conditions are presented. Both of the ISL fixtures exhibited significantly greater IPIL values compared to the GRAS fixture. The right ear of the ISL-1 fixture displayed 14.9 dB, 13.9 dB, 14.7 dB while the right ear of the ISL-2 fixture exhibited 8.4 dB, 19.5 dB, 18.4 dB greater IPIL compared to the right ear of the GRAS fixture at the 132-dB, 150-dB and 168-dB impulse levels. The left ear of the ISL-2 fixture displayed 9.6 dB, 22.5 dB, 19.2 dB greater IPIL compared to the left ear of the GRAS fixture at all three impulse levels.

Discussion

Acoustic Test Fixture Ear Canal Design

The dual-ear ISL-2 fixture was the first one constructed according to the ANSI/ASA S12.42-2010 standard's specifications. The standard specifies that the ear canal extension added to the coupler shall be 14±1 mm in length. The ISL-2 ATF ear canal extensions permitted earplug insertions of about 12 mm. Subsequent ISL-2 ATFs were built with ear canal extensions that permitted about 16 mm of earplug insertion depth.

The ear canal of the GRAS fixture has two segments: a 4 mm section that is a part of the pinna and a 14 mm ear canal extension. The pinna is made from a rubber material that simulated skin and the opening of the canal was 4 mm thick and which is disconnected from the ear canal extension of the IEC 60711 coupler. The GRAS ear canal extension is built from a turned steel tube and has a simulated skin lining. When attached to the IEC 60711 coupler, the ear canal length was 18 mm. The inner diameter of the GRAS ear canal extension is 7.5 mm. The ISL-2 canal is also cylindrical, but the entire length is effectively a thick-walled silicon tube with an inner diameter of 7.5 mm. The ISL-2 canal has a shorter section near the coupler that is thicker and is coupled to the IEC 60711 simulator differently than the GRAS ear canal extension. That is, the GRAS extension is steel and mates directly to steel. The ISL canal is silicon and has a different material that is mounted to a flange on the case surrounding the IEC 60711 coupler.

Longer ear canal extensions should yield greater IPIL estimates with formable earplugs and some flanged earplugs due to the greater contact area with the walls of the ear canal extension. Although the current study did not evaluate a formable earplug, unpublished impulse data collected by NIOSH at the US Army Aeromedical Research Laboratory at Fort Rucker indicated that the IPIL increased with the insertion depth. In general, the insertion depth is a critical factor for achieving an adequate amount of protection when exposed to continuous noise (Murphy et al., 2009; Murphy et al., 2011); therefore, insertion depth should be critical to providing protection from impulse noise.

In this study, molded triple-flanged earplugs were evaluated. The third flange (most lateral) was larger than the diameter of the ear canal and could wrinkle if forced into the ATF ear canal of the ISL fixtures. For the GRAS fixture, the earplugs could be inserted such that the third flange was in contact with the tragus and the floor of the concha. During testing, care was exercised to avoid having visible wrinkles of the flanges, which could introduce an acoustic leak. Flanged earplugs fitted into the shortest ear canal of the single-ear ISL ATF may not have had a good seal with the ear canal extension (Murphy, 2003; Murphy et al., 2012). In two other unpublished studies conducted at Fort Rucker (2011) and at EARCAL (2014), the IPIL observed for flanged earplugs exhibited slightly less attenuation for the longer ear canals of the 18 mm GRAS 45 CB and the 16 mm ISL-2 ATFs than for the 13-mm ISL-2 ATF. One might conjecture that the additional length of the ear canal permitted a deeper insertion of the plug, which in turn produced more wrinkling of the second and third flanges of the earplugs. In the ISL-2 ATF, the third flange of the earplug makes contact, but because it cannot be inserted too far (due to the grid on the IEC 60711 coupler), the wrinkling is prevented.

In order to accurately assess the impact of ear canal length on the performance of the hearing protection devices, ideally, it would be desirable to have an access to acoustic test fixture in which the length of the ear canal can be varied by 3-4 different sizes. Since this may not be economically feasible, the next best option would be to evaluate the effect of insertion depth of the earplug with the dual–ear GRAS or ISL fixtures, which have longer canal lengths to explore. This future study that we are proposing would provide some insight in the designing of an acoustic test fixture that allows us to test protection on a fixture that better simulates a human ear canal.

Acoustic Test Fixture Pinna

One of the issues identified by this study with the GRAS fixture was associated with the design of the pinna. The earlier model (version 1) of the GRAS fixture tested in this study had a raised contour “bump” that was anterior (in front of) to the pinna; as well the back of the pinna had more material that prevented the pinna from collapsing if an earmuff was in contact with it. The bump anterior to the pinna on the GRAS fixture prevented the earmuff from appropriately sealing around the pinna, resulting in poor overall performance for the earmuff. GRAS improved the overall design of its fixture in versions 2 and 3 by removing the material from the back of the pinna and reduced the contour in the front, thus eliminating the bump anterior to the pinna. These modifications also improved the friction fitting associated with the connection of the pinna to the head. In this study, when the ISL fixtures were tested with the TacticalPro earmuff, they exhibited greater IPILs compared to the GRAS fixture. These differences may be attributed to the pinna design differences, the ISL fixtures did not have a raised contour anterior to the pinna and the pinna was connected firmly to the head. Overall, the IPIL values measured (Table 10) in this study for the ISL fixtures using the TacticalPro earmuff were generally 3 to 7 dB greater than the GRAS fixture across all three impulse levels.

Impulse Waveform Configuration

All three fixtures exhibited similar waveforms for the ETYPlugs earplugs at all three impulse levels. This earplug offered comparable hearing protection across the three fixtures at the 132-dB impulse level. However, at the 150 and 168-dB impulse levels, the two dual-ear fixtures yielded greater protection in comparison to the single-ear ISL fixture. The lesser protection offered by the single-ear ISL fixture may be attributed to its shorter ear canal length.

All three fixtures displayed similar waveforms with the EB1 earplugs but the waveform morphology changed with impulse level. At the 132-dB level, the electronic circuitry of the EB1 earplug initially attenuated the peak but then released the compression, which restored unity gain and audibility of the reverberant impulse levels. The EB1 earplug exhibited the same trend at the 150-dB level. However, at the 168-dB level, the peaks were attenuated but the rest of the signal or electronics had less of an effect so that the response resembled the ETYPlugs earplug at the 168-dB level. For a given level, the reductions were comparable across all three fixtures.

The GRAS fixture exhibited more low-frequency components in the waveforms measured for the TacticalPro earmuff at the 132 and 150-dB levels. The high-frequency content can be observed in all three fixtures, but the large, low-frequency oscillation dominated the responses measured with the GRAS fixture. The two ISL fixtures also have a low-frequency component, but the high-frequency components are more evident in their waveforms. Consequently, the ISL fixtures consistently yielded greater IPILs for the TacticalPro earmuff than what was measured for the GRAS fixture.

Similarly in the dual protector condition, the low-frequency components were more evident in the GRAS fixture than in the ISL fixtures. The GRAS fixture exhibited more low-frequency components in the waveforms measured for the TacticalPro earmuff at 132-dB levels than were observed for the ISL fixtures. The dual-ear ISL-2 fixture exhibited the highest IPILs for the double protection condition followed by the single-ear ISL-1 and then the GRAS fixture (Table 10). Generally, the IPIL differences measured between the three fixtures were statistically significant at all three impulse levels. In summary, the dual-protection offers significantly greater protection with the ISL fixtures than compared to the GRAS fixture. However, the dual protection when worn by a real person would be affected by the limits of bone-conduction. Based upon the analysis in a previous EPHB report, IPIL levels would be limited to 41 dB, the limits of bone conduction for continuous noise (Khan et al. 2013; Berger et al. 2003).

Acoustic Test Fixture Heating

Two of the ATFs in this study provided heat to the ear canal while the single-ear ISL-1 ATF did not have heating. The ANSI/ASA S12.42-2010 standard states "The couplers and ATF shall be maintained at a temperature of 37±2 °C during testing because of the influence of temperature on the dynamic characteristics of elastomeric materials used in earplugs and earmuff cushions".

The process of heating the fixtures varies by manufacturer. For the GRAS fixture, the heating is applied to a solid aluminum block, which represents the bulk of the fixture. The GRAS pinna has a metal base plate that contacts the aluminum block and heat is efficiently transferred to the artificial skin surrounding the pinna. For the ISL fixture, the heating is applied to the capsule that encloses the IEC 60711 coupler within the solid acrylic fixture. The coupler transfers heat to a copper ring that is integral to the mount of the ear canal extension.

During testing of the HPDs on the GRAS fixture, earmuff cushions and earplugs are in direct contact with a heated surface. The protectors' material properties, if they are affected by the heating, will more closely simulate the situation for the fitting on an actual human head. During testing of the HPDs on the ISL-2 fixture, the cushions of the earmuff do not appear to receive any appreciable temperature increase. The temperature of the earplugs, however, is increased by the heat transfer to the ISL-2 ear canal.

A future experiment should be developed to assess the impact of fixture heating on the attenuation of the earplug. This research will identify whether the protection offered by the HPDs to hunters, law enforcement and soldiers in winter and summer is similar or different. Temperature of the hearing protectors and ear canals could be measured with a non-contact infrared thermometer. The heating of the surface surrounding the pinnae could be imaged with an infrared camera and the temperature of earmuff cushions could be measured.

Single versus Double Protection

NIOSH recommends that dual hearing protection be used in typical continuous noise levels found in manufacturing and construction when exposures exceed 105 dB SPL. At these levels, the acoustics of attenuation are governed by linear processes. The effective attenuation for two protectors worn simultaneously is not simply the addition of the noise reduction ratings for the earplug and the earmuff. Instead, the effective attenuation is a complex addition of the attenuations in conjunction with the noise spectrum. The simplest approach is to add 5 dB to the highest NRR rating for the muff or plug as recommended by Abel and Armstrong (1992).

For the case of dual protection, the US Army has used a multiplicative factor of 20 to account for the additional protection when dual protectors are worn. In the MIL-STD 1474D, the allowable number of rounds is computed based upon the peak pressure level and the B-duration (the time for the envelope of the impulse(s) to decay by 20 dB). The additional factor of 20 equates to adding 6.5 dB to the maximum permissible peak sound pressure exposure level.

For the ISL fixtures, the occupational 5-dB rule of thumb and the MIL-STD 1474D 6.5-dB allowance both underestimate the actual attenuation performance measured on the fixture. The dual-ear ISL-2 fixture measured a 14-dB increase in the IPIL and about a 10-dB increase for the single-ear ISL-1 fixture. For the GRAS fixture, the only exhibited appreciable increases of about 5 to 8 dB for the 132-dB impulse level.

The analysis of the double protection conditions is potentially complicated by three factors affecting the findings of this study.

First, the isolation of the GRAS fixture's acoustic pathway appears to be significantly less than the ISL design. During comparison of the IPIL results for the GRAS fixture with the dual-protector condition versus the TacticalPro earmuff only, it reveals there is a minimal increase of approximately 1.5 to 0.5 dB across the three impulse levels. Whereas, the same condition for the ISL fixtures yield approximately 8 to 11 dB improvement for the dual protection condition.

Second, the concept of summation that is typically applied in lower, continuous noise sources does not seem to work for these high-level impulse sound sources. For instance, the 168-dB impulse is reduced by about 35 dB for the TacticalPro earmuff. The impulse level presented to the ETYPlugs is going to be about 133 dB. Furthermore, the impulse at the ETYPlugs will be altered by its transition through the earmuff and no longer has a fully developed wavefront.

Third, the earmuffs have greater attenuation for the high-frequencies than they do for the low-frequencies. The differential filtering effect means that frequency dependent attenuation combined with the spectra of any incident impulses could produce radically different results, which are a function of the protectors used and the spectrum of the impulse source.

Conclusions

The ETYPlugs earplug consistently displayed greater IPIL (2-3 dB) when measured on the two dual-ear fixtures compared to the single-ear fixture at the 132, 150 and 168-dB impulse levels. The EB-1 BlastPLG earplugs also exhibited greater IPIL (2-8 dB) when measured on the two dual-ear fixtures versus the single-ear fixture at the 150 and 168-dB impulse levels. The longer ear canal length associated with the two dual-ear fixtures appears to provide better performance for the earplugs in comparison to the single-ear fixture ISL-1 with the shorter ear canal.

The TacticalPro earmuff measured the greatest IPIL with the single-ear ISL-1 and dual-ear ISL-2, and the least IPIL with the dual-ear GRAS ATF. Generally, the single-ear ISL-1 and the dual-ear ISL-2 fixtures also offered better protection at all three impulse levels using the double-protection in comparison to the GRAS fixture. The greater IPIL values obtained on the ISL fixtures using the earmuff and double-protection may be attributed to differences in head and pinna designs.

This study raises several technical issues related to the use of ATFs for assessing the performance of HPDs on impulse noise. The effect of ear canal length on the attenuation of earplugs should be investigated in greater detail. This study considered only premolded earplugs. The effect of insertion depth on IPIL should be investigated with formable earplugs and, if possible, with flanged earplugs. The effect of the heating of the acoustic test fixtures on the performances of the hearing protection devices should also be evaluated.

This and previous NIOSH studies have demonstrated the A-duration requirements as stated in the ANSI S12.42-2010 standard are not representative of firearm noise characteristics. The short A-durations produced by small-caliber firearms have greater high frequency spectral content than those produced by acoustic shock tubes. Thus, future revisions of the ANSI S12.42 standard should include compensation for the effect of the spectral content on the IPIL measurement.

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Tables

Table 1: Etymotic Research ETYPlugs® Earplug IPIL data

The minimum, maximum, mean and the standard deviation values were computed for each impulse level from five samples of each HPD with five fittings for each sample and with three impulses produced for each fitting resulting in generation of 75 rifle shots. The numbers in this table were computed using arithmetic means.

Sample Number	GRAS 2 Fixture Free-Field	Left IPIL	Right IPIL	Avg IPIL	ISL 2 Fixture Free-Field	Left IPIL	Right IPIL	Avg IPIL	ISL 1 Fixture Free-Field	Right IPIL
132 dB peak SPL										
1	132.3	20.8	20.1	20.4	132.5	19.7	19.0	19.3	132.8	16.9
2	132.1	19.6	18.9	19.3	132.1	19.4	18.5	18.9	132.4	17.0
3	132.1	20.5	19.8	20.2	132.5	20.4	18.0	19.2	132.2	17.6
4	132.8	19.4	20.6	20.0	133.2	19.3	19.0	19.1	132.5	17.6
5	132.8	21.1	19.6	20.3	132.1	19.4	18.6	19.0	132.8	18.4
Mean	132.4	20.3	19.8	20.1	132.5	19.7	18.6	19.2	132.5	17.5
Std. Dev	1.2	1.2	2.0	1.7	0.9	1.1	1.5	1.5	0.6	1.1
Min	129.6	16.3	13.3	13.3	130.6	16.2	14.0	14.0	130.9	14.6
Max	136.2	22.3	26.5	26.5	135.1	22.1	22.0	22.4	133.6	20.7
150 dB peak SPL										
1	149.9	21.3	23.1	22.2	149.7	22.5	22.1	22.3	149.8	19.2
2	149.6	20.4	22.2	21.3	149.7	21.6	22.2	21.9	149.8	19.0
3	149.7	20.9	22.0	21.4	149.6	21.4	22.4	21.9	149.7	18.5
4	150.0	20.5	22.3	21.4	149.6	21.3	22.1	21.7	149.8	19.3
5	150.0	20.8	22.7	21.7	149.7	21.8	22.2	22.0	149.7	19.9
Mean	149.8	20.8	22.5	21.7	149.7	21.7	22.2	22.1	149.8	19.2
Std. Dev	0.4	0.6	1.2	1.5	0.5	0.8	0.7	1.2	0.5	0.7
Min	149.0	19.7	19.3	19.3	148.4	20.1	20.4	20.1	148.7	17.5
Max	150.6	22.0	25.5	27.4	150.7	24.0	24.2	27.6	150.8	20.7
168 dB peak SPL										
1	169.7	26.5	26.1	26.3	170.3	28.2	27.5	27.9	169.9	24.9
2	169.6	26.5	26.9	26.7	170.1	27.5	28.0	27.8	169.8	24.8
3	169.9	26.8	27.0	26.9	170.1	27.1	27.5	27.3	170.2	25.0
4	169.9	26.1	27.0	26.5	170.0	26.5	28.0	27.2	170.2	25.1
5	169.8	26.8	26.8	26.8	170.3	27.5	27.6	27.5	170.1	25.2
Mean	169.8	26.5	26.8	26.6	170.2	27.4	27.7	27.5	170.0	25.0
Std. Dev	0.4	0.9	0.7	0.9	0.4	0.6	0.9	0.8	0.4	0.2
Min	168.8	25.1	25.7	25.1	169.1	25.9	24.6	24.6	169.0	24.4
Max	170.5	28.8	29.0	29.0	171.1	29.2	28.9	29.2	171.1	25.5

Table 2: Etymotic EB-1 BlastPLG™ earplugs IPIL earplug Data
The minimum, maximum, mean and the standard deviation values were computed for each impulse level from five samples of each HPD with five fittings for each sample and with three impulses produced for each fitting resulting in generation of 75 rifle shots. The numbers in this table were computed using arithmetic means.

Sample Number	GRAS 2 Fixture				ISL 2 Fixture				ISL 1 Fixture	
	Free-Field	Left IPIL	Right IPIL	Avg IPIL	Free-Field	Left IPIL	Right IPIL	Avg IPIL	Free-Field	Right IPIL
132 dB peak SPL										
1	132.3	18.7	19.6	19.2	132.2	14.4	16.0	15.2	132.7	18.3
2	132.6	18.1	19.8	18.9	133.4	15.0	16.7	15.9	132.3	18.0
3	132.5	19.0	19.3	19.1	132.7	17.5	17.0	17.3	132.6	18.5
4	132.7	17.9	19.9	18.9	133.2	16.8	17.2	17.0	132.2	19.6
5	132.9	17.6	19.8	18.7	132.6	34.6*	17.2	25.9	132.1	19.0
Mean	132.6	18.2	19.7	19.0	132.8	15.9	16.8	16.4	132.4	18.7
Std. Dev	0.8	1.0	1.0	1.2	1.1	7.7	1.1	5.7	0.7	1.1
Min	130.3	15.6	17.6	15.6	130.5	12.4	13.9	12.4	130.4	16.5
Max	135.0	20.3	21.7	21.7	136.4	37.9	19.9	37.9	134.2	20.7
150 dB peak SPL										
1	150.1	33.9	36.2	35.1	149.7	32.4	33.8	33.1	149.5	31.9
2	149.5	31.5	35.0	33.3	149.7	31.6	33.6	32.6	149.5	32.3
3	150.0	33.1	35.0	34.1	149.7	32.0	33.4	32.7	149.7	32.7
4	149.8	33.3	35.8	34.5	149.7	31.6	33.3	32.4	149.7	32.5
5	149.9	31.8	36.1	33.9	149.7	31.3	33.8	32.5	149.8	31.0
Mean	149.8	32.7	35.6	34.2	149.7	31.8	33.6	32.7	149.6	32.1
Std. Dev	0.4	1.3	1.0	1.8	0.4	0.8	0.6	1.2	0.4	1.2
Min	148.9	29.2	32.1	29.2	148.8	29.5	32.1	29.5	148.6	28.9
Max	150.7	35.7	37.2	37.2	150.9	33.7	34.9	34.9	150.7	34.5
168 dB peak SPL										
1	169.7	46.0	46.5	46.3	170.0	43.8	45.8	44.8	170.0	37.3
2	169.7	39.0	50.4	44.7	169.9	37.6	46.0	41.8	169.8	37.0
3	170.1	46.5	47.5	47.0	170.8	44.7	44.6	44.7	169.8	38.3
4	169.8	44.7	45.9	45.3	170.3	39.2	43.9	41.6	170.2	38.4
5	170.0	48.1	47.2	47.7	170.2	42.9	43.6	43.2	170.1	38.1
Mean	169.9	44.9	47.5	46.2	170.2	41.6	44.8	43.2	170.0	37.8
Std. Dev	0.4	3.3	2.5	3.2	0.6	3.0	1.2	2.8	0.4	1.0
Min	168.8	38.4	44.8	38.4	169.0	36.8	42.2	36.8	168.8	35.3
Max	170.9	49.1	54.1	54.1	171.7	46.5	47.2	47.2	170.7	39.4

*This sample has been excluded from the overall analysis of this study due to the malfunction of the protector.

Table 3: 3M™ Peltor™ TacticalPro Communications Headset Earmuff IPIL Data
The minimum, maximum, mean and the standard deviation values were computed for each impulse level from five samples of each HPD with five fittings for each sample and with three impulses produced for each fitting resulting in generation of 75 rifle shots. The numbers in this table were computed using arithmetic means.

Sample Number	GRAS 2 Fixture				ISL 2 Fixture				ISL 1 Fixture	
	Free-Field	Left IPIL	Right IPIL	Avg IPIL	Free-Field	Left IPIL	Right IPIL	Avg IPIL	Free-Field	Right IPIL
132 dB peak SPL										
1	132.7	23.9	18.8	21.4	132.1	26.6	28.0	27.3	132.8	28.4
2	132.9	26.0	20.2	23.1	132.1	28.2	26.8	27.5	132.5	31.0
3	133.2	29.0	19.3	24.1	132.1	27.1	23.8	25.4	132.5	29.0
4	132.4	31.7	22.3	27.0	132.7	22.9	23.8	23.3	132.4	29.3
5	132.3	22.8	18.4	20.6	133.0	29.8	28.9	29.4	132.5	32.4
Mean	132.7	26.7	19.8	23.2	132.4	26.9	26.3	26.6	132.5	30.0
Std. Dev	1.0	5.3	3.3	5.6	1.1	4.1	3.1	3.6	0.6	2.0
Min	131.0	16.9	13.9	13.9	130.5	14.8	16.3	14.8	130.2	26.0
Max	136.6	34.3	27.1	34.3	134.9	32.8	33.4	33.4	133.7	34.3
150 dB peak SPL										
1	149.9	36.2	39.8	38.0	149.8	36.5	38.5	37.5	149.8	38.9
2	149.7	34.5	30.4	32.5	149.8	39.6	38.3	38.9	149.1	35.5
3	149.8	22.4	26.2	24.3	149.6	38.0	38.4	38.2	149.7	36.1
4	150.0	29.5	37.3	33.4	149.6	37.8	39.1	38.4	149.6	38.3
5	149.8	38.3	30.2	34.3	149.6	39.6	38.2	38.9	149.9	37.4
Mean	149.8	32.2	32.8	32.5	149.7	38.3	38.5	38.4	149.6	37.3
Std. Dev	0.4	6.6	6.3	6.5	0.4	1.7	1.2	1.5	0.5	1.9
Min	148.9	19.8	23.6	19.8	148.8	34.4	34.9	34.4	148.6	32.9
Max	150.6	40.6	41.9	41.9	150.6	41.8	41.0	41.8	150.7	41.1
168 dB peak SPL										
1	169.1	37.5	35.4	36.4	169.9	45.5	46.0	45.8	169.8	43.9
2	169.7	39.9	43.6	41.7	170.0	43.1	43.3	43.2	169.8	44.0
3	170.1	35.3	44.9	40.1	171.1	42.3	45.5	43.9	169.6	42.4
4	170.0	36.6	42.6	39.6	170.1	45.3	45.6	45.4	169.9	46.2
5	170.1	39.6	35.2	37.4	170.1	38.6	43.6	41.1	169.9	45.4
Mean	169.8	37.8	40.3	39.1	170.2	43.0	44.8	43.9	169.8	44.4
Std. Dev	0.6	5.4	5.2	5.5	0.6	2.9	1.4	2.5	0.4	1.5
Min	168.2	24.7	29.3	24.7	169.2	34.8	41.2	34.8	168.9	41.5
Max	170.8	44.3	45.9	45.9	171.5	46.7	47.8	47.8	170.8	47.7

Table 4: Dual protection ETYPlugs® Earplug and TacticalPro Earmuff IPIL Data
The minimum, maximum, mean and the standard deviation values were computed for each impulse level from five samples of each HPD with five fittings for each sample and with three impulses produced for each fitting resulting in generation of 75 rifle shots. The numbers in this table were computed using arithmetic means.

Sample Number	GRAS 2 Fixture				ISL 2 Fixture				ISL 1 Fixture	
	Free-Field	Left IPIL	Right IPIL	Avg IPIL	Free-Field	Left IPIL	Right IPIL	Avg IPIL	Free-Field	Right IPIL
132 dB peak SPL										
1	132.5	29.6	30.9	30.2	132.4	38.3	32.9	35.6	132.5	41.6
2	132.6	31.4	28.3	29.8	132.4	39.4	35.3	37.3	132.5	41.9
3	132.3	31.3	24.9	28.1	132.6	41.7	35.8	38.8	132.6	41.1
4	133.1	31.0	27.2	29.1	132.6	38.9	34.2	36.5	132.5	42.1
5	132.4	29.1	22.9	26.0	132.8	40.1	36.1	38.1	132.8	40.3
Mean	132.6	30.1	26.5	28.3	132.6	39.7	34.9	37.3	132.6	41.4
Std. Dev	1.0	2.5	3.7	3.7	0.9	4.0	4.5	4.9	0.5	1.4
Min	129.8	24.7	17.4	17.4	129.9	29.7	25.1	25.1	131.2	38.7
Max	134.9	36.9	35.5	36.9	135.2	45.5	44.3	45.5	133.9	45.7
150 dB peak SPL										
1	150.1	29.7	34.8	32.2	149.9	53.9	53.8	53.9	149.6	48.7
2	149.8	29.9	29.0	29.5	149.7	51.9	51.5	51.7	149.6	42.7
3	150.0	30.7	31.1	30.9	149.7	52.4	50.6	51.5	149.6	43.5
4	149.9	30.3	34.1	32.2	149.5	54.0	52.0	53.0	149.7	48.8
5	150.0	31.8	33.8	32.8	149.7	52.6	52.6	52.6	149.6	48.8
Mean	149.9	30.5	32.6	31.5	149.7	53.0	52.1	52.5	149.6	46.5
Std. Dev	0.3	2.0	3.2	2.8	0.5	1.6	1.6	1.7	0.5	3.0
Min	149.3	26.2	26.1	26.1	148.5	48.5	48.9	48.5	148.3	40.3
Max	150.7	36.3	41.4	41.4	150.6	55.7	55.2	55.7	151.2	52.2
168 dB peak SPL										
1	169.6	37.6	41.7	39.6	170.1	62.5	61.1	61.8	169.8	55.7
2	169.8	38.4	38.5	38.4	171.2	58.6	58.1	58.4	169.9	53.9
3	170.3	40.0	39.8	39.9	170.1	56.6	56.3	56.5	170.1	54.0
4	170.0	41.3	38.1	39.7	170.3	58.4	55.4	56.9	170.3	53.4
5	170.0	40.9	39.6	40.3	170.3	57.0	58.5	57.7	170.1	54.1
Mean	169.9	39.6	39.5	39.6	170.4	58.6	57.9	58.3	170.1	54.2
Std. Dev	0.5	3.3	2.5	2.9	0.6	3.8	2.6	3.3	0.4	1.3
Min	168.8	35.0	35.0	35.0	169.1	51.4	51.1	51.1	169.2	51.3
Max	170.8	47.5	47.2	47.5	171.7	64.5	61.9	64.5	171.1	57.7

Table 5: Comparison of ears' least squares means (predicted marginal means) of IPIL for nominal impulses of 132dB, 150-dB and 168-dB. The estimated difference is the least squares means for the left ear minus that for the right ear. Use of the Turkey adjustment ensures that the overall alpha is 0.05.

Hearing Protection Devices	Impulse Level (dB)	Acoustic Test Fixture	Estimated Differences ($IPIL_{Left}$-$IPIL_{Right}$)	Tukey Adj p	95% Conf. Interval (Tukey Adj)	
ETYPlugs Earplugs	132	GRAS	0.5	1.0	-0.7	1.7
	150	GRAS	-1.7	<.0001	2.4	1.0
	168	GRAS	-0.2	1.0	-0.9	0.4
	132	ISL2	1.1	0.02	0.07	2.0
	150	ISL2	-0.5	0.3	-1.0	0.1
	168	ISL2	-0.3	0.9	-0.9	0.2
EB1 BlastPLG Earplugs	132	GRAS	-1.4	<.0001	-2.2	-0.7
	150	GRAS	-2.9	<.0001	-3.8	-2.0
	168	GRAS	-2.6	0.005	-4.8	-0.5
	132	ISL2	-0.9	0.3	-2.0	0.2
	150	ISL2	-1.8	<.0001	-2.3	1.3
	168	ISL2	-3.1	<.0001	-4.8	-1.4
TacticalPro Earmuffs	132	GRAS	6.9	<.0001	3.6	10.2
	150	GRAS	-0.6	1.0	-5.4	4.2
	168	GRAS	-2.5	0.7	-6.5	1.4
	132	ISL2	0.7	1.0	-2.0	3.4
	150	ISL2	-0.2	1.0	-1.3	0.9
	168	ISL2	-1.8	0.02	-3.5	-0.1
Dual Protection ETYPlugs Earplug and TacticalPro Earmuff	132	GRAS	3.6	0.03	0.2	7.0
	150	GRAS	-2.1	0.02	-4.1	-0.1
	168	GRAS	0.1	1.0	-2.1	2.3
	132	ISL2	4.8	.0001	1.6	8.0
	150	ISL2	0.9	0.5	-0.3	2.1
	168	ISL2	0.8	1.0	-1.7	3.2

Table 6: Comparison of fixtures' least squares means for ETYPlugs earplugs. The estimated difference is the least squares means of the fixture 1 minus that of fixture 2. The use of the Tukey adjustment ensures that the overall alpha is 0.05.

Impulse Levels (dB)	Acoustic Test Fixture Ear ATF1	Acoustic Test Fixture Ear ATF2	Estimated Difference ($IPIL_{ATF1}$-$IPIL_{AFT2}$)	Tukey Adj p	95 % Conf. Interval (Tukey Adj)	
132	ISL1 Right	ISL2 Right	-1.1	0.005	-2.0	-0.2
132	ISL1 Right	GRAS Right	-2.3	<.0001	-3.3	-1.2
132	ISL2 Left	GRAS Left	-0.6	0.9	-1.7	0.5
132	ISL2 Right	GRAS Right	-1.2	0.02	-2.3	0.08
150	ISL1 Right	ISL2 Right	-3.0	<.0001	-3.6	-2.5
150	ISL1 Right	GRAS Right	-3.3	<.0001	-3.9	2.7
150	ISL2 Left	GRAS Left	1.0	0.0002	0.3	1.6
150	ISL2 Right	GRAS Right	-0.3	1.0	-0.9	0.4
168	ISL1 Right	ISL2 Right	-2.7	<.0001	-3.1	-2.3
168	ISL1 Right	GRAS Right	-1.8	<.0001	-2.2	-1.3
168	ISL2 Left	GRAS Left	0.8	0.0004	0.2	1.4
168	ISL2 Right	GRAS Right	0.9	<.0001	0.3	1.5

Note: GRAS is dual-ear GRAS fixture, ISL1 is single-ear ISL fixture and ISL2 is dual-ear ISL Fixture.

Table 7: Comparison of fixtures' least squares means for EB1earplugs. The estimated difference is the least squares means of the fixture 1 minus that of fixture 2. The use of the Tukey adjustment ensures that the overall alpha is 0.05.

Impulse Levels (dB)	Acoustic Test Fixture Ear ATF1	Acoustic Test Fixture Ear ATF2	Estimated Difference ($IPIL_{ATF1}$-$IPIL_{ATF2}$)	Tukey Adj p	95 % Conf. Interval (Tukey Adj)	
132	ISL1 right	ISL2 right	1.9	<.0001	0.9	2.8
132	ISL1 right	GRAS right	-1.0	0.002	-1.8	0.2
132	ISL2 left	GRAS left	-2.3	<.0001	-3.3	-1.3
132	ISL2 right	GRAS right	-2.9	<.0001	-3.8	-2.0
150	ISL1 right	ISL2 right	-1.5	<.0001	-2.2	-0.8
150	ISL1 right	GRAS right	-3.5	<.0001	-4.4	-2.7
150	ISL2 left	GRAS left	-0.9	0.001	-1.7	-0.2
150	ISL2 right	GRAS right	-2.0	<.0001	-2.8	-1.3
168	ISL1 right	ISL2 right	-7.0	<.0001	-8.3	-5.7
168	ISL1 right	GRAS right	-9.7	<.0001	-11.3	-8.1
168	ISL2 left	GRAS left	-3.2	<.0001	-5.2	-1.3
168	ISL2 right	GRAS right	-2.7	.0005	-4.7	-0.8

Note: GRAS is dual-ear GRAS fixture, ISL1 is single-ear ISL fixture and ISL2 is dual-ear ISL Fixture.

Table 8: Comparison of fixtures' least squares means for TacticalPro earmuffs. The estimated difference is the difference between the least squares means (predicted marginal means) of the IPIL for the two fixtures. The use of the Tukey adjustment ensures that the overall alpha is 0.05.

Impulse Levels (dB)	Acoustic Test Fixture Ear ATF1	Acoustic Test Fixture Ear ATF2	Estimated Difference ($IPIL_{ATF1}$-$IPIL_{ATF2}$)	Tukey Adj p	95 % Conf. Interval (Tukey Adj)	
132	ISL1 right	ISL2 right	3.7	<.0001	1.6	5.9
132	ISL1 right	GRAS right	10.2	<.0001	7.7	12.8
132	ISL2 left	GRAS left	0.2	1.0	-2.8	3.2
132	ISL2 right	GRAS right	6.5	<.0001	3.5	9.5
150	ISL1 right	ISL2 right	-1.2	0.07	-2.5	0.05
150	ISL1 right	GRAS right	4.5	0.002	0.9	8.0
150	ISL2 left	GRAS left	6.1	<.0001	2.6	9.6
150	ISL2 right	GRAS right	5.7	<.0001	2.2	9.2
168	ISL1 right	ISL2 right	-0.4	1.0	-1.8	1.1
168	ISL1 right	GRAS right	4.1	0.0005	1.2	7.0
168	ISL2 left	GRAS left	5.2	<.0001	2.1	8.2
168	ISL2 right	GRAS right	4.5	0.0002	1.4	7.5

Note: GRAS is dual-ear GRAS fixture, ISL1 is single-ear ISL fixture and ISL2 is dual-ear ISL Fixture

Table 9: Comparison of fixtures' least squares means for Dual Protection for ETYPlugs earplug and TacticalPro earmuff. The estimated difference is the difference between the least squares means (predicted marginal means) of the IPIL for the fixtures. The use of the Tukey adjustment ensures that the overall alpha is 0.05.

Impulse Levels (dB)	Acoustic Test Fixture Ear ATF1	Acoustic Test Fixture Ear ATF2	Estimated Difference ($IPIL_{ATF1}$-$IPIL_{ATF2}$)	Tukey Adj p	95 % Conf. Interval (Tukey Adj)	
132	ISL1 right	ISL2 right	6.5	<.0001	4.2	8.9
132	ISL1 right	GRAS right	14.9	<.0001	12.4	17.4
132	ISL2 left	GRAS left	9.6	<.0001	6.3	12.9
132	ISL2 right	GRAS right	8.4	<.0001	5.1	11.6
150	ISL1 right	ISL2 right	-5.6	<.0001	-7.4	-3.8
150	ISL1 right	GRAS right	14.0	<.0001	11.9	16.1
150	ISL2 left	GRAS left	22.5	<.0001	20.9	24.1
150	ISL2 right	GRAS right	19.5	<.0001	17.9	21.2
168	ISL1 right	ISL2 right	-3.7	<.0001	-5.5	-1.8
168	ISL1 right	GRAS right	14.7	<.0001	13.0	16.4
168	ISL2 left	GRAS left	19.0	<.0001	16.7	21.3
168	ISL2 right	GRAS right	18.4	<.0001	16.0	20.7

Note: GRAS IS dual-ear GRAS fixture, ISL1 is single-ear ISL fixture and ISL2 is dual-ear ISL Fixture.

Table 10: Comparisons of least squares means for IPILs for the single and dual-protections using the dual-ear GRAS fixture (GRAS), dual-ear ISL fixture (ISL2) and singe-ear ISL fixture (ISL1).

Protector	Impulse Levels (dB)	GRAS	ISL2	ISL1
ETYPlugs Earplug	132	20.0	19.1	17.5
	150	21.6	22.0	19.2
	168	26.6	27.5	25.0
TacticalPro Earmuff	132	23.3	26.6	30.0
	150	32.5	38.4	37.3
	168	39.1	43.9	44.4
Dual-protection with ETYPlugs Earplug & TacticalPro Earmuff	132	28.3	37.3	41.4
	150	31.5	52.5	46.5
	168	39.6	58.3	54.2

Figures

Figure 1: Three models of hearing protection tested in this study. The Etymotic Research EB1 BlastPLG™ earplug, an electronic level-limiting earplug tested at the 0-dB or unity gain setting. The Etymotic Research ETYPlugs® earplug is a uniform attenuation earplug. The 3M™ Peltor™ TacticalPro™ Communication Headset earmuffs have five volume settings and were tested at the third setting which nominally provided unity gain. The ETYPlugs® and TacticalPro™ (at unity gain) were tested as a dual hearing protector combination.

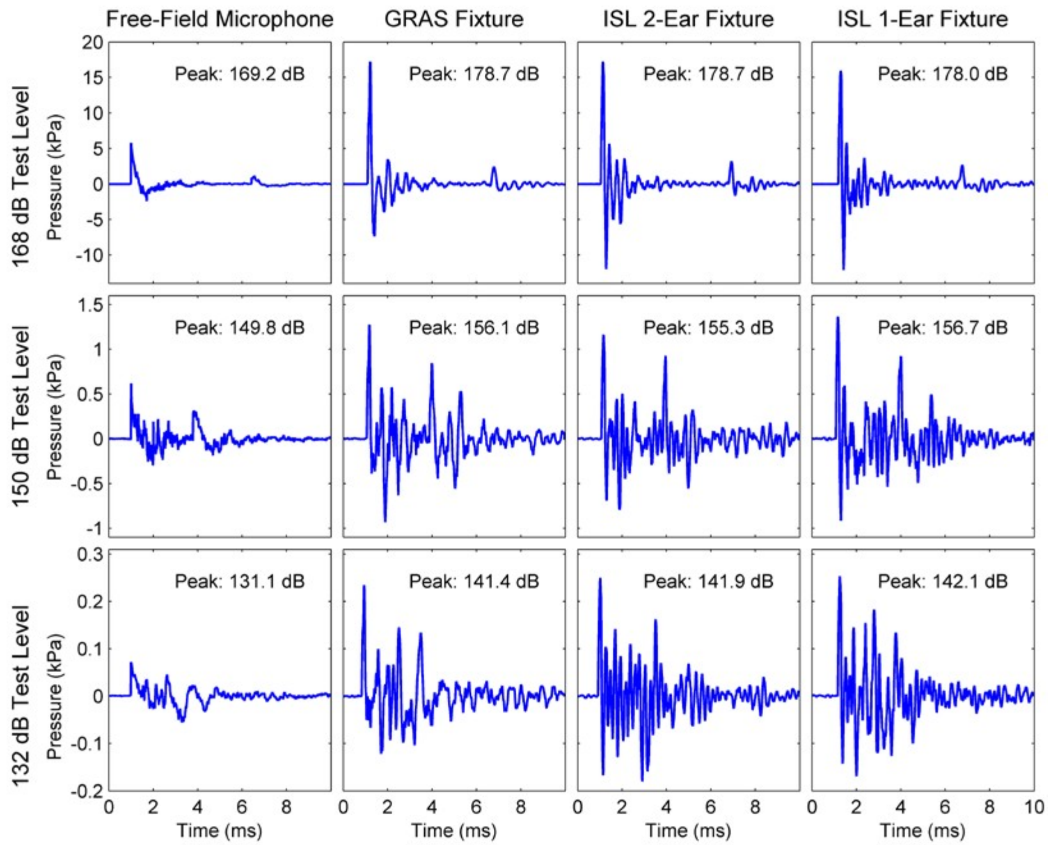

Figure 2: Example unoccluded waveforms measured from the field microphones and acoustic test fixtures for the 132-dB, 150-dB and 168-dB impulse levels. The free-field microphones were fixed in the same location while the three fixtures were rotated through all three positions.

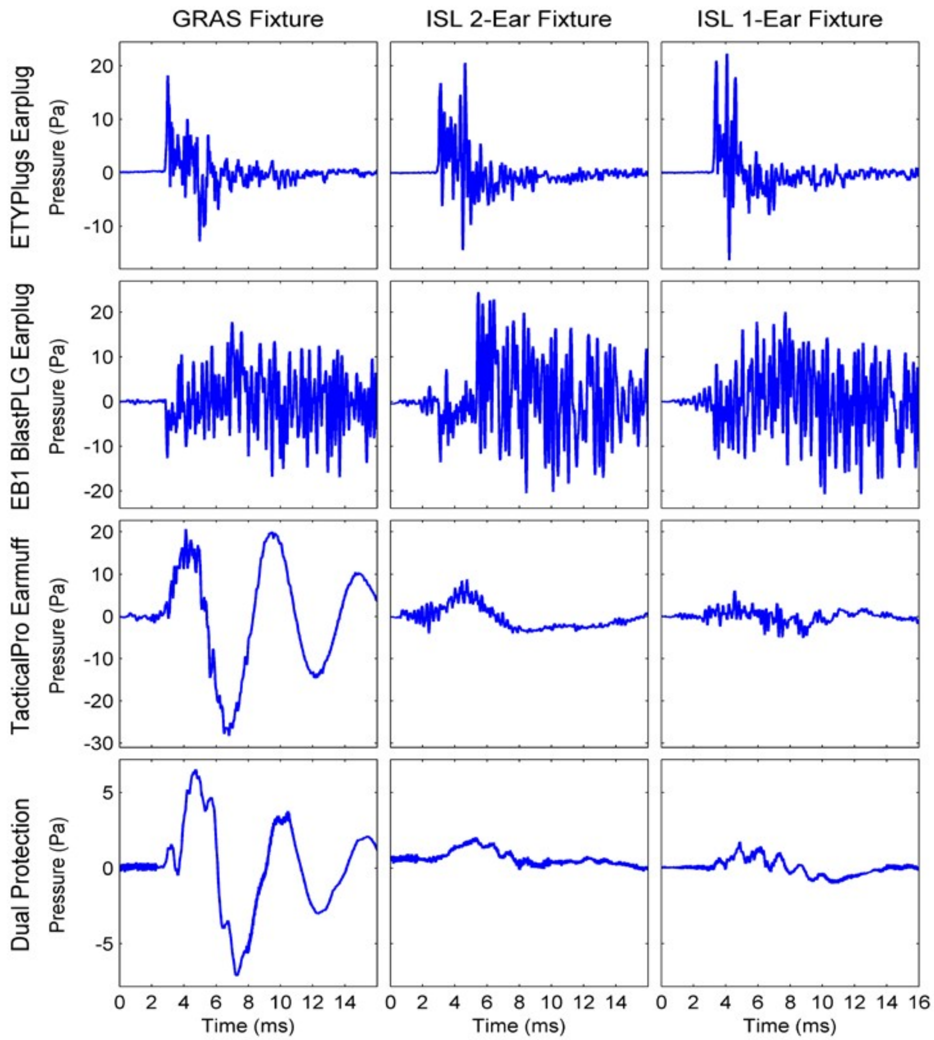

Figure 3: Example occluded waveforms measured at the 132-dB impulse level for the dual-ear GRAS, dual-ear ISL and single-ear ISL fixtures using ETYPlugs earplug, EB1 BlastPLG earplug, Peltor TacticalPro earmuff and Dual Protection with TacticalPro earmuff combined with ETYPlugs earplug.

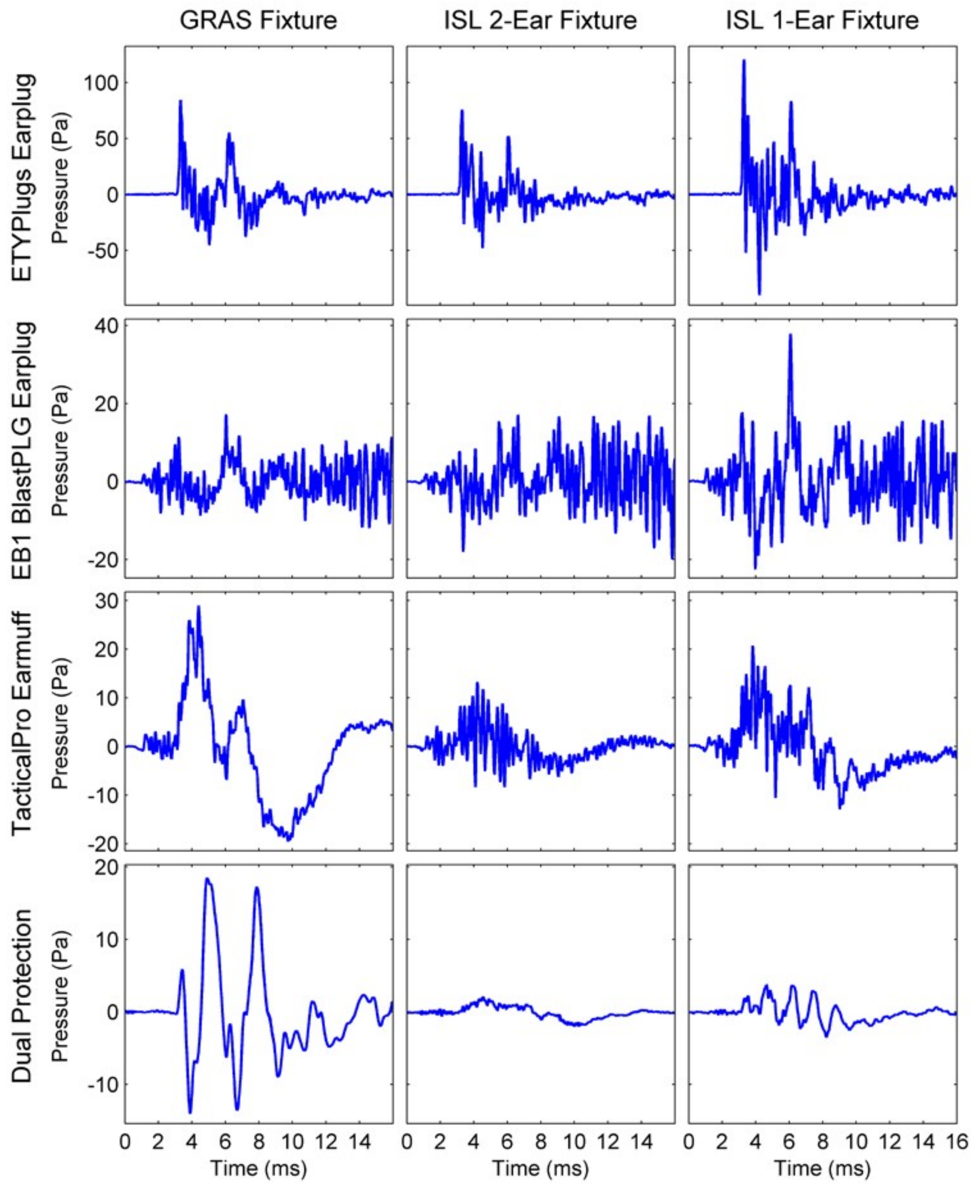

Figure 4: Example occluded waveforms measured at the 150-dB impulse level for the dual-ear GRAS, dual-ear ISL and single-ear ISL fixtures using ETYPlugs earplug, EB1 BlastPLG earplug, Peltor TacticalPro earmuff and Dual Protection with TacticalPro earmuff combined with ETYPlugs earplug.

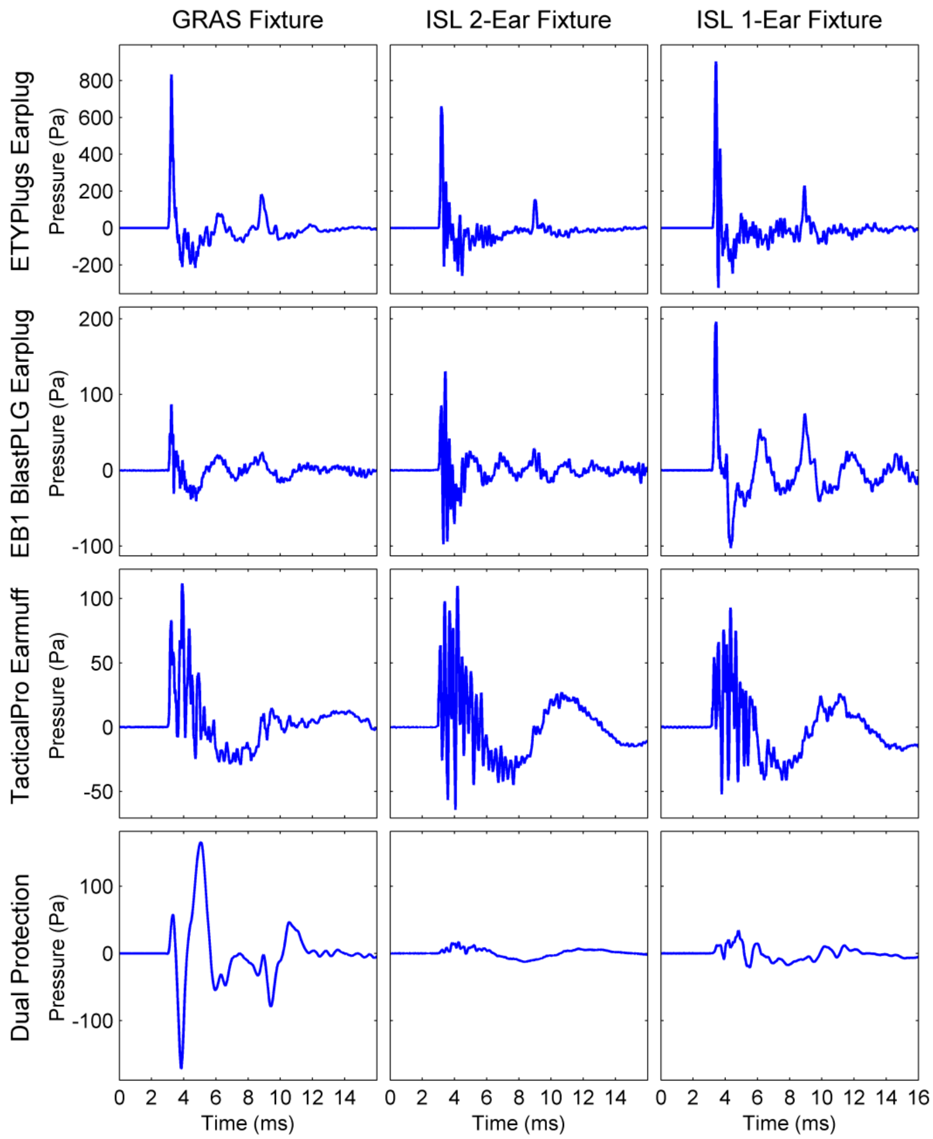

Figure 5: Example occluded waveforms measured at the 168-dB impulse level for the dual-ear GRAS, dual-ear ISL and single-ear ISL fixtures using ETYPlugs earplug, EB1 BlastPLG earplug, Peltor TacticalPro earmuff and Dual Protection with TacticalPro earmuff combined with ETYPlugs earplug.

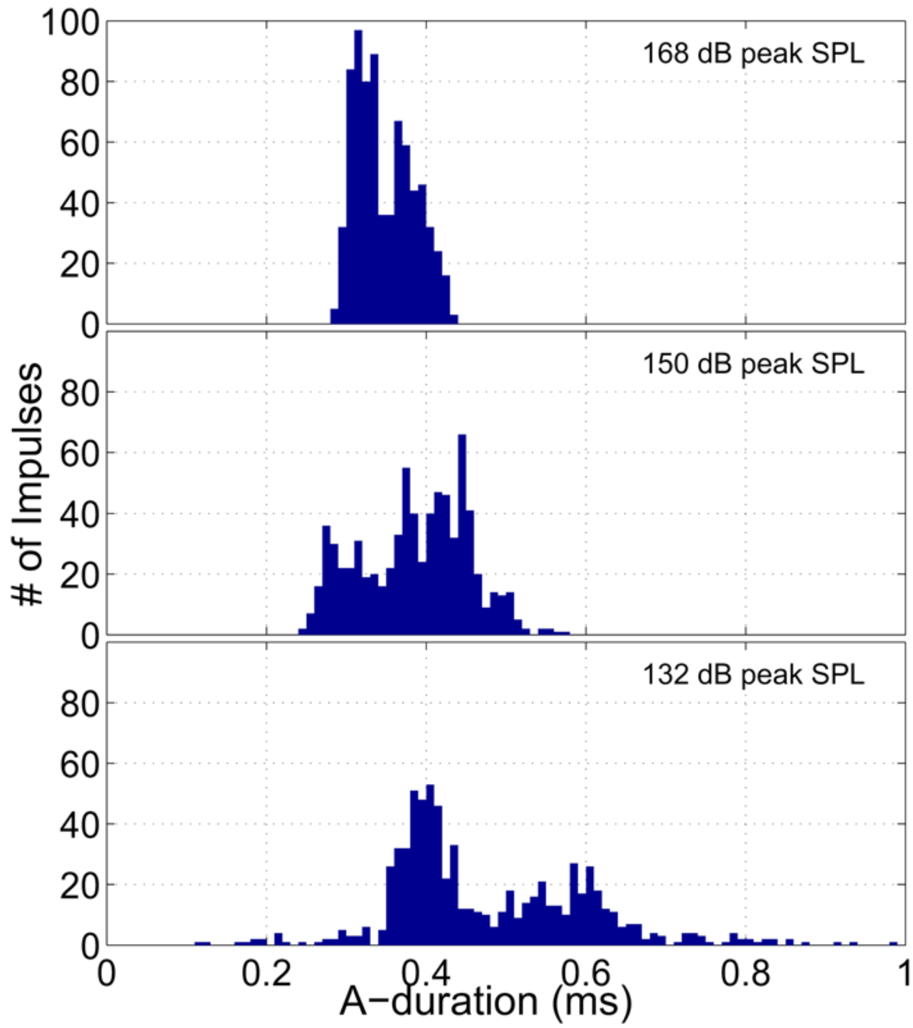

Figure 6 A-duration data for the impulses produced by .223 caliber Colt AR-15 rifle were measured with the free-field microphones. The A-durations varied between 0.24 to 0.45 ms at the 168-dB impulse level, 0.24 to 0.58 ms at the 150-dB impulse level and 0.11 to 0.98 ms at the 132-dB impulse level.

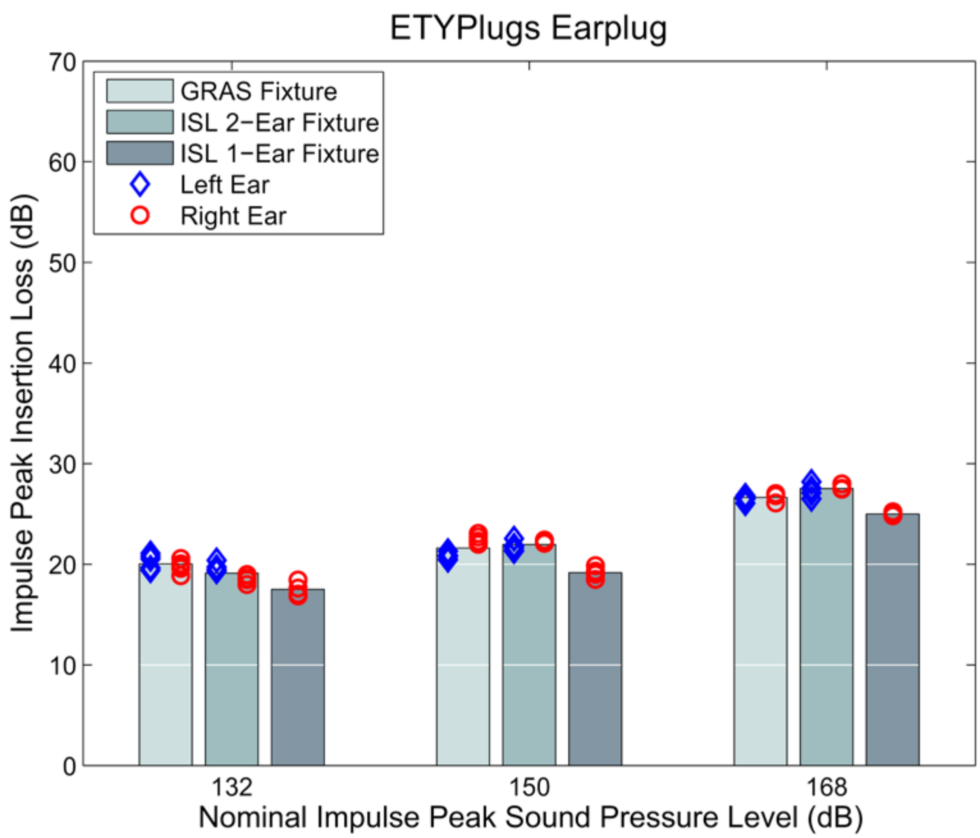

Figure 7: Etymotic Research ETYPlugs® Earplug IPIL results. The bars correspond to the average IPIL for each test level as measured on each fixture. The diamonds and circles are the average IPIL values for the left and right ears of each sample.

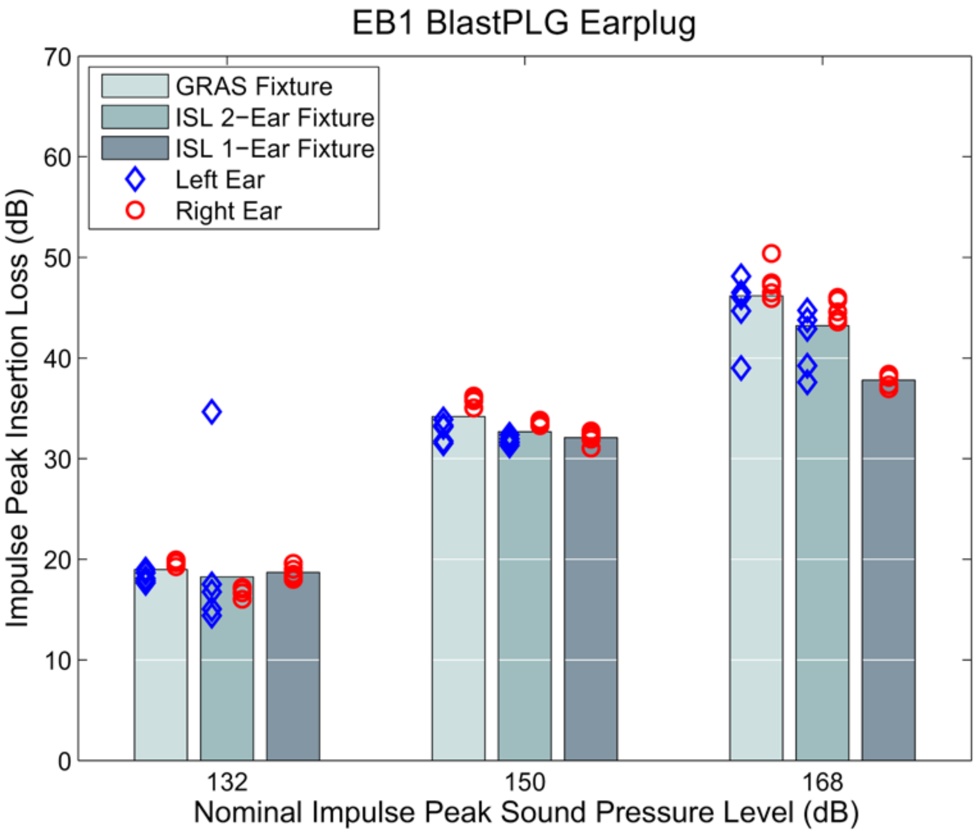

Figure 8: EB1 BlastPLG Earplug IPIL results. The bars correspond to the average IPIL for each test level as measured on each fixture. The diamonds and circles are the average IPIL values for the left and right ears of each sample.

Note: Sample 5 associated with the left ear of the dual-ear ISL fixture has been excluded from the study due to the malfunction of the protector.

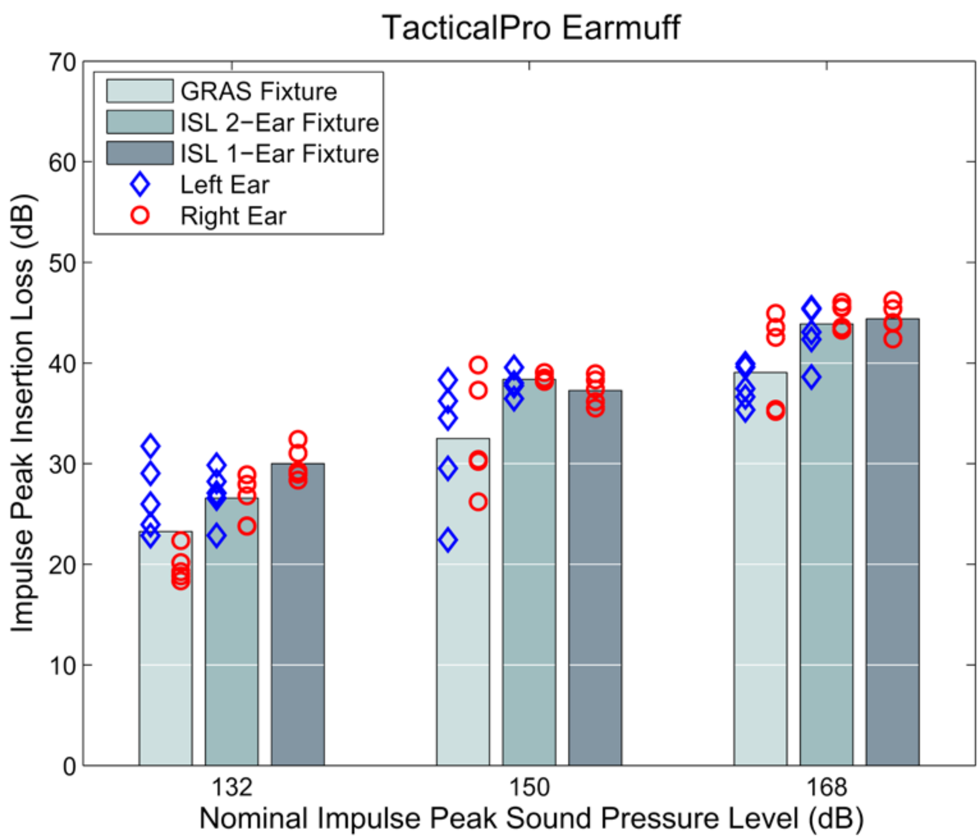

Figure 9: 3M™ Peltor™ TacticalPro Communications Headset (tested with electronics on and set to unity gain) IPIL results. The bars correspond to the average IPIL for each test level as measured on each fixture. The diamonds and circles are the average IPIL values for the left and right ears of each sample.

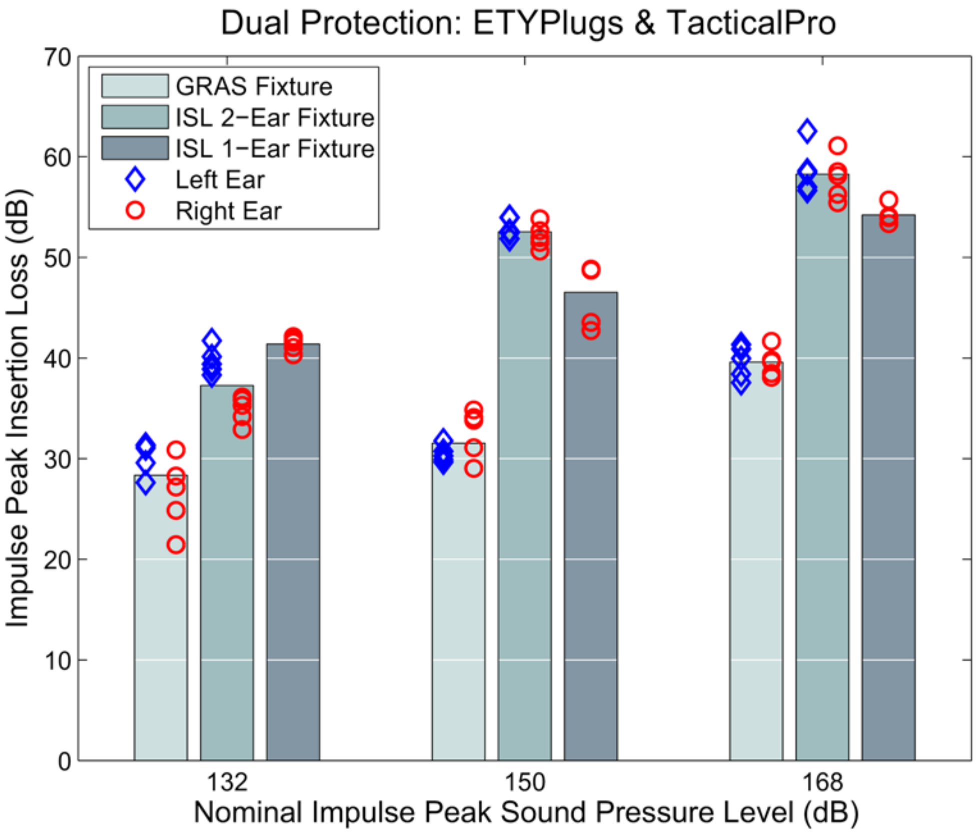

Figure 10: Dual protection Etymotic Research ETYPlugs® Earplug and 3M™ Peltor™ TacticalPro Communications Headset IPIL results. The bars correspond to the average IPIL for each test level as measured on each fixture. The diamonds and circles are the average IPIL values for the left and right ears of each sample.

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