In-Depth Survey Report

Comparison of Two Acoustic Test Fixtures for Measurement of Impulse Peak Insertion Loss

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Abstract

In 2012, NIOSH partnered with 3M and VIAcoustics for a field study at the 3M™ E-A-RCAL Laboratory (Indianapolis, IN) to measure Impulse Peak Insertion Loss (IPIL) with four hearing protector conditions. IPIL characterizes the noise reduction provided by a hearing protection device in response to high-level impulse signals. The IPIL value is the difference between the maximum sound pressure levels in open-ear and closed-ear conditions. Two data acquisition systems gathered readings from a blast probe and two models of the same acoustic test fixture (ATF): one model from E-A-RCAL and one from NIOSH. The ATFs and blast probe were placed in front of a horn attached to an acoustic shock tube, which produced acoustic impulses at various test levels. Four hearing protection devices (3M™ E-A-R™ Single-Ended Combat Arms™ Earplug, Etymotic Research ETYPlugs® Earplug, 3M™ Peltor™ TacticalPro Communications Headset, and a dual-protector ETYPlugs® earplug with TacticalPro earmuff) were evaluated at nominal peak impulse levels of 132, 150, and 168 decibels (dB).

The data were simultaneously recorded by two acquisition systems and did not differ significantly between systems. However, statistically significant differences were observed between the IPIL estimates from the E-A-RCAL and NIOSH ATFs and between the left and right ears of each ATF. The IPIL measured by the left ear of the E-A-RCAL ATF was significantly higher than that of the right ear. The NIOSH ATF did not show such trends, even though the two ATFs were nearly identical. The orientation and location of the ATFs with respect to the wavefront expanding from the horn were significant factors on the impulse level at the two fixtures and between the ears of the fixtures. For the majority of the protectors and impulse levels, the differences between the average IPIL measurements for the two ATFs were statistically significant, indicating real differences possibly due to the fixtures' position or construction. To ensure repeatability, the IPIL estimates were computed with two separate implementations of the ANSI/ASA S12.42-2010 standard. Analyzing the full-length waveforms recorded during the study with the NIOSH MATLAB IPIL calculator and the VIAcoustics IPILA software yielded identical IPIL estimates.

Introduction

In 2009, the U.S. Environmental Protection Agency (EPA) proposed the use of a new metric to characterize the performance of hearing protection devices in high-level impulse noise (EPA 2009). The EPA proposed methods to evaluate a protector's performance over a range of impulse levels at nominal values of 132-, 150-, and 168-decibels peak sound pressure level (dB peak SPL). The peak levels are allowed to vary from target levels within a range of ±2 dB, and the initial overpressure (A-duration) can vary between 0.5 and 2.5 milliseconds (ms). The EPA provided its proposed methodology to Working Group 11 of the American National Standards Institute (ANSI) Subcommittee 12 for Noise, which subsequently developed the recently approved standard ANSI/ASA S12.42-2010.

In previous field studies, NIOSH has evaluated different acoustic test fixtures (ATFs), hearing protectors, and impulse noise sources. The purpose of this study, performed at the 3M™ E-A-RCAL Laboratory (Indianapolis, IN), was to utilize a more controlled laboratory environment to investigate the Impulse Peak Insertion Loss (IPIL) performance of a variety of protectors. The study compared the output of two different data acquisition systems and two models of the same ATF as well as the IPIL calculated with two different implementations of the ANSI/ASA S12.42-2010 standard methods.

The data acquisition and impulse generation equipment at the 3M™ E-A-RCAL Laboratory is similar to that at the NIOSH Impulse Noise Laboratory, and the laboratory space is acoustically treated and large enough to permit measurements over a wide range of impulse levels. With the exception of slightly longer ear canals in the E-A-RCAL fixture, the E-A-RCAL and NIOSH ATFs are identical.

This report analyzes and summarizes the IPIL data collected on four hearing protector conditions from July 30 through August 2, 2012. The study was jointly conducted with staff from 3M (Elliott Berger and Mike Stergar) and VIAcoustics (Jeff Schmitt). Dr. William Ahroon, of the U.S. Army Aeromedical Research Laboratories, observed the tests.

Methods

Repeated measurements of an impulse noise source are made with an ATF in both the unoccluded (open) and occluded (protected) conditions, with impulses of 132, 150, and 168 dB peak SPL. In addition to the ATF, an external field microphone simultaneously records the free-field impulse at each trial; the peak sound pressure level of the free-field impulse constitutes the impulse test level. A series of measurements with the fixture unoccluded establishes acoustic transfer functions between the field microphone and the right and left ears of the fixture. With the fixture occluded, the unoccluded fixture response is estimated by applying these field-to-fixture transfer functions to the waveform recorded by the field microphone. Since the field to fixture transfer functions are level dependent, they must be measured separately for each impulse level at which the protector is to be tested. The difference between the estimated maximum absolute peak sound pressure level of the unoccluded condition and the measured maximum of the occluded condition constitutes the IPIL of the hearing protector under test (ANSI/ASA S12.42, 2010; Murphy et al., 2012).

In this study, the impulse peak insertion loss was measured for four combinations of hearing protection devices using two acoustic test fixtures with a single blast probe constituting the field microphone. Two different data acquisition systems sampled the impulse waveforms produced by an acoustic shock tube and horn.

Acoustic Test Fixtures

G.R.A.S. Sound & Vibration (GRAS) and the French-German Research Institute of Saint Louis (ISL) both developed ATFs that complied with the ANSI/ASA S12.42-2010 standard in response to a competitive contract advertised by NIOSH. The NIOSH ISL ATF was delivered in April 2011. 3M E-A-RCAL received their ISL fixture in December 2012. Both E-A-RCAL and NIOSH own a GRAS model 45CB fixture developed for testing to the ANSI/ASA S12.42-2010 standard. For this study, the ISL fixtures were chosen to facilitate comparison of the results to previously published data collected with the ISL fixtures (Berger and Hamery, 2008; Murphy and Tubbs, 2007).

The ISL ATFs met the dimensional requirements of ANSI/ASA S12.42-2010 standard for testing HPDs in impulse noise. The ATFs had earcanals with a length of 14±1 millimeters (mm) and diameter of 7.5 to 8.0 mm. The earcanals, pinnae, and area surrounding the pinnae were flexible and had a Shore OO durometer rating of 58 when at room temperature and 68 when heated to body temperature, 37 °C. The pinna material was stiffer than the standard's specification of a durometer rating between 30 and 60.

The ISL ATFs were 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 1/4" GRAS Type 40BP microphone and GRAS Type 26AC microphone preamplifier and was powered by a GRAS Type 12AA power module. The length of the external portion of the NIOSH ISL earcanal was 13 mm and the E-A-RCAL ISL earcanal was 16 mm. In an earlier evaluation of the NIOSH ATF, E-A-RCAL scientists noted that foam earplugs could not be fully inserted in a 13 mm earcanal. Thus, the E-A-RCAL fixture was designed to accommodate slightly longer earcanals to allow deeper insertion of foam earplugs. A GRAS 67SB blast probe was used to measure the free field impulses. The blast probe was equipped with a GRAS 1/8" Type 40DP microphone and GRAS Type 26AC microphone preamplifier and was powered with a GRAS Type 12AA power module.

Acoustic Impulse Source

An acoustic shock tube designed and developed by NIOSH generated the acoustic impulses. Khan et al. (2012) describe the use and operation of the acoustic shock tube. The overall dimensions of the acoustic shock tube were approximately 62 inches long, 56 inches high, and 16 inches wide. It consisted of three major components: (1) The compressed airflow system pressurized the shock tube to the desired level, (2) The shock tube pressure chamber contained the pressurized air and generated an impulse when the membrane burst, (3) The acoustic horn provided impedance matching between the exhaust tube and the open air.

A membrane material (foil, paper, plastic film) was clamped between flanges with sufficient force to create an airtight seal in the pressure chamber. The chamber was pressurized with air and a trigger activated a lance to burst the membrane. A shock wave impulse formed in the exhaust tube as the sudden release of compressed air propagated along the tube and into the acoustic horn. The horn reduced the reflection of energy at the interface between the horn and the room (open air). Previous studies at the NIOSH Impulse Noise Laboratory have shown that the horn also minimizes a downstream flow-induced turbulent vortex, which is especially prevalent for chamber pressures above approximately 20 pounds per square inch gauge (psig) when the horn is absent.

In this study, the 132 dB impulses were generated by bursting 0.5 mil polyester films at a pressure of 4.4 psig. The 150 dB impulses were generated by bursting 1-mil polyester films at 11 psig. The 168 dB impulses were generated by bursting 3.0 mil polyester films at 47 psig. The impulses generated by the acoustic shock tube were amplified by a catenoidal horn for all three levels.

Data Acquisition System

NIOSH and 3M used identical National Instruments (NI) PXI-1042 data acquisition chassis with NI PXI-4462 data acquisition boards. The NI PXI-4462 boards had four channels, resolution of 24 bits, input ranges of ±42 Volts, and were capable of sampling signals at 204.8 kHz. The NIOSH system had two PXI-4462 boards while the 3M system had one board. In order to facilitate comparisons between the two systems, both sampling rates were set to 102.4 kHz because the 3M system was configured for that rate. The blast probe microphone triggered the sampling for both data acquisition systems.

The NIOSH data acquisition system was controlled by the NIOSH Sound Power VI program running in LabView. The NIOSH Sound Power VI program saved the sampled acoustic pressure data in Pascals to a structured MATLAB .mat binary file for post-processing in MATLAB. The NIOSH system collected a 1.0-second sample for each impulse, with a pre-trigger interval of 0.1 second. Triggering for the Sound Power VI was accurate to within about 5 milliseconds (ms).

The 3M E-A-RCAL data acquisition system was controlled by the Trident software developed by Nelson Acoustics and VIAcoustics. Trident stores its data in a

Microsoft .wav binary format that incorporates a scaling factor for converting .wav levels to Pascals. The Trident sample window was 0.5 seconds, also with a 0.1-second pre-trigger interval. The Trident system used a block-based triggering and data acquisition scheme. Blocks of 0.1 seconds were sampled and then evaluated for the presence of an impulse during that block. If an impulse was detected, the previous block and four additional blocks were saved to memory. This scheme ensured that the impulse would be found in the second block of 0.1 seconds. The block size was configurable to longer or shorter times; however, the recommended setting of 0.1 seconds was used.

In both data acquisition systems, the blast probe and the ATF microphones were sampled simultaneously. For both data acquisition systems, the blast probe was on channel 1 and the left and right ears of the 3M E-A-RCAL ISL ATF were connected to channels 2 and 3, respectively. The left and right ears of the NIOSH ATF were connected to channels 4 and 5 of the NIOSH data acquisition system only.

Equipment Setup

The blast probe was positioned in front of the center of the mouth of the catenoidal horn. The ATF positions were determined by extending a tape measure from the center of the mouth of the catenoidal horn to the right and left ears of each ATF. The ATFs were aligned to point to the center of the mouth of the horn by sighting along the seam of each fixture. The distance between the blast probe microphone and the center of the mouth of the catenoidal horn was 1.02 meters. The distance from the concha of the NIOSH ATF’s left ear to the center of the mouth of the catenoidal horn was 1.2 meters while the distance from the concha of the E-A-RCAL ATF’s right ear to the center of the mouth of the catenoidal horn was 1.13 meters. The two ATFs and the blast probe were not moved during this study since all three impulse levels could be achieved by adjusting the thickness of the membrane material and operating pressure of the shock tube. Figure 1 illustrates the setup of the blast probe and the two ISL ATFs relative to the catenoidal horn.

The test fixtures were heated to approximately 37°C, prior to the calibration of the ATF microphones. The blast probe’s 1/8” microphone was calibrated with a GRAS Type 42AP pistonphone using a GR1423 calibration adapter. The GR1423 adaptor was designed to permit the 1/8” microphone, with the depth collar necessary for the blast probe construction, to be inserted into the calibrator. An external calibration adapter GR1462K is now included with the blast probe assembly that eliminates the need to disassemble the probe to gain access to the 1/8” microphone and to insert the microphone into the GR1423 adapter. The ATF microphones were calibrated using the ISL-provided earcanal to 1/2” calibration adapter that allows the microphones to be calibrated in the fixture.

Hearing Protection Devices

In this study, the 3M™ E-A-R™ Single-Ended Combat Arms™ Earplug (tested with its valve open, hereafter referred to as the Combat Arms earplug), Etymotic Research ETYPlugs® Earplug (formerly known as the ER-20 High-Fidelity Earplug, referred to here as the ETYPlugs earplug), 3M™ Peltor™ TacticalPro Communications Headset (referred to as the TacticalPro earmuff, tested with its electronics on and set to unity gain), and a dual-protection combination of the ETYPlugs earplug and the TacticalPro earmuff were evaluated on the NIOSH and E-A-RCAL ATFs. Figure 2 illustrates these protectors. All of the earmuffs and earplugs were fitted on the ATFs by WJ Murphy to maintain a consistent fitting technique.

During May 2011, the NIOSH Hearing Loss Prevention Team conducted a field study to evaluate three acoustic test fixtures: the NIOSH ISL 2-eared fixture, an older NIOSH 1-eared ISL fixture with short earcanals and no heating, and the recently developed GRAS 45CB test fixture with the first version of the GRAS pinna inserts. During this field study, a gunshot provided the impulse noise source and three hearing protectors were selected: the Etymotic Research EB1 Electronic BlastPLG™ Earplug, the ETYPlugs earplug and the TacticalPro earmuff. The ETYPlugs earplug and TacticalPro earmuff were also tested in a dual-protection combination (Murphy et al., 2012).

The three hearing protection devices tested at E-A-RCAL were selected to compare the results with the earlier study and to compare to other studies conducted with different acoustic shock tube noise sources. The ETYPlugs earplug provides a moderate level of attenuation and has a noise reduction rating (NRR) of 16 dB. The TacticalPro earmuff is an electronic earmuff with an NRR of 26 dB. The TacticalPro earmuff was tested with its electronics set to unity gain by selecting the middle of five possible volume settings of the earmuff. For electronic HPDs, the unity gain volume setting 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 these two protectors is consistent with the NIOSH recommendation and was expected to realize an IPIL uncorrected above 40 dB (NIOSH, 2009).

The Combat Arms earplug was evaluated following the recommendation of 3M E-A-RCAL staff. This earplug contains a level-dependent acoustic filter that attenuates high levels while allowing low levels to pass through relatively unchanged. Previous versions of the Combat Arms earplug were double ended; one end contained such a filter element while the other end provided constant protection. The single-ended version of the Combat Arms earplug tested in this study offers a unique rocker cover that allows the user to enable or disable the filter by simply opening or closing a valve with a fingertip, thus eliminating the need to remove the plug. In the open-valve condition, this earplug's NRR is 7 dB; in the closed-valve condition, the NRR is 23 dB. The plug was inserted into the earcanals of the ATFs and tests were conducted with the valve open. In this configuration, the earplug provides low attenuation at the 132 dB peak level and higher attenuation at the 150 and 168 dB impulse levels.

Data Analysis

The ANSI/ASA S12.42-2010 impulse signal analysis is summarized below. 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, $H_{\text{ATF-FF},L,n}(\text{f})$, exists

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

where $P_{\text{FF},L,n}(\text{f})$ and $P_{\text{ATF},L,n}(\text{f})$ 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:

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

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

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

where $p'_{\text{ATF},L,n}(t)$ denotes the estimated unoccluded ATF pressure waveform, $P_{\text{FF},L,n}(t)$ 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,

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

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.

Slope of the IPIL with Impulse Level

The IPIL changes with the level of the impulse that interacts with the protector and fixture. Allen and Berger (1983) and Berger and Hamery (2008) described the response function of protectors with an orifice or valve that provides increased acoustic resistance with increasing level. Murphy (2003) described the response of several protectors using a linear regression over the range of levels at which the product was tested. In this study, linear regressions were used to describe the dependence of IPIL on level by fitting the following:

$$\mathrm{IPIL}(L,i) = mP(L,i) + b, \tag{5}$$

$$\mathrm{IPIL}(L,i) = \frac{1}{J}\sum_{j=1}^{J} \mathrm{IPIL}(L,i,j), \tag{6}$$

$$P(L,i) = \frac{1}{J}\sum_{j=1}^{J} P(L,i,j), \tag{7}$$

where m and b are the slope and intercept of the regression, and $\mathrm{IPIL}(L, i)$ and $P(L, i)$ are the IPIL and free-field peak level for a specific protector sample (i) at the nominal test level L.

Bone-Conduction Correction

In the ANSI/ASA S12.42-2010 standard, bone-conduction corrections are used to adjust the attenuation measured on a fixture in continuous noise to the limits of sound transmission through the human skin and skull to directly excite the cochlea. Bone-conduction limits have been reported for attenuation measurements with continuous presentation of 1/3rd octave bands of noise (OBN) (Zwislocki, 1957; Berger, 1983; Berger et al., 2003). The most recent of these investigations was used in the ANSI/ASA S12.42-2010 standard to establish the bone-conduction limit corrections as a function of frequency,

$$\mathrm{TA}_{\mathrm{BC-corrected}}(f) = -10\log_{10}\left(10^{-\mathrm{TA}_{\mathrm{uncorrected}}(f)/10} + 10^{-\mathrm{BCL}(f)/10}\right), \tag{8}$$

where TA is the total attenuation and BCL is the bone-conduction limit given below for a given octave band.

Frequency (Hz)	125	250	500	1000	2000	4000	8000
Head Not Covered	50	57	61	49	41	50	50
Head enclosed by helmet with face shield	50	57	61	54	49	60	61

For impulse noise, these limits have not been investigated. From preliminary investigations with an artificial head that contains a hydrophone and accelerometers (Clavier et al. 2012), the transmission of the impulse via bone conduction appeared to be linear within the range of impulse levels used in this investigation (130 to 170 dB peak SPL).

In this study, the ATFs were uncovered and the 41 dB limit at 2000 Hz was applied to the IPIL data. Equation (8) was modified to use the uncorrected IPIL levels instead of total attenuation and the BCL limiting level was set to 41 dB,

$$\mathrm{IPIL}_{\mathrm{BC-corrected}} = -10\log_{10}\left(10^{-\,\mathrm{IPIL}_{\mathrm{uncorrected}}/10} + 10^{-41/10}\right). \quad (9)$$

For most of the IPIL estimates in this report, bone conduction provided only a minimal change in the IPIL values. Only for the 168 dB impulses in the dual protection condition were the corrections more than 1 dB.

Results

3M™ E-A-R™ Single-Ended Combat Arms™ Earplug

The performance data for the Combat Arms earplug using the E-A-RCAL and NIOSH ATFs are presented in Table 1 and illustrated in Figure 3. The summary results for the Combat Arms earplug and the other three protectors are given in Table 5. The IPILs for the valve-open condition were between about 7 and 12 dB for the 132 dB impulses, between 19 and 25 dB for the 150 dB impulses, and between 30 and 33 dB for the 168 dB impulses. For the 132 dB impulses, achieving a sharp onset impulse was difficult not only for the Combat Arms earplug, but for all protectors that were tested. While every effort was made to produce impulses that complied with the ANSI/ASA S12.42-2010 standard, more often than not, the levels were exceeded by 1 or 2 decibels. For the Combat Arms earplug, six out of ten low-level impulses were outside the acceptable range of 130-134 dB but the middle and high impulse levels were all within the acceptable ranges of 148-152 dB and 166-170 dB.

Measurements of IPIL from the E-A-RCAL ATF exhibited average differences between the left and right ears ($\mathrm{IPIL}_{\mathrm{Left}} - \mathrm{IPIL}_{\mathrm{Right}}$) of 1.5 dB for the 132-dB impulses, 2.0 dB for the 150 dB impulses and 3.1 dB for the 168-dB impulses. For the 132 and 150-dB impulse levels, the IPIL differences were statistically significant using the Student's t-test ($p < 0.05$) and the left ear exhibited more IPIL than the right ear.

The average IPIL differences between the left and right ears ($\mathrm{IPIL}_{\mathrm{Left}} - \mathrm{IPIL}_{\mathrm{Right}}$) of the NIOSH ATF were -0.3 dB for the 132-dB impulses, -0.2 dB for the 150 dB impulses and 0.8 dB for the 168-dB impulses. These IPIL differences were statistically significant at all three impulse levels ($p < 0.05$).

The average IPIL estimates were compared between the E-A-RCAL and NIOSH ATFs ($\mathrm{IPIL}_{\mathrm{EARCAL}} - \mathrm{IPIL}_{\mathrm{NIOSH}}$). The average IPIL differences 1.9 dB at the 132-dB level, 1.2 dB at the 150-dB level, and 1.2 dB at the 168-dB level. The average IPIL differences between the two fixtures were statistically significant for 132 and 150 dB impulse levels ($p < 0.05$).

Etymotic Research ETYPlugs® Earplug

The detailed IPIL results for the ETYPlugs earplug are presented in Table 2 and illustrated in Figure 4. Six of the ten 132 dB impulses were above the 134 dB maximum limit but did not exceed 135.0 dB peak level. The impulses generated at the 150 dB and 168 dB levels were within the specifications of the ANSI/ASA S12.42-2010 standard.

For the E-A-RCAL ATF, the average IPIL differences between the left and right ears ($IPIL_{Left} – IPIL_{Right}$) were 1.3 dB for the 132 dB impulses, 1.7 dB for the 150 dB impulses and 1.1 dB for the 168 dB impulses. For all impulse levels, the IPIL differences were statistically significant using the Student's t-test ($p < 0.05$) and the left ear exhibited more IPIL than the right ear.

The average IPIL differences between the left and right ears ($IPIL_{Left} – IPIL_{Right}$) of the NIOSH ATF were -0.9 dB for the 132 dB impulses, -0.5 dB for the 150 dB impulses, and 0.3 dB for the 168 dB impulses. These IPIL differences were statistically significant at the 132 dB impulse level ($p < 0.05$).

The average IPIL estimates were compared between the E-A-RCAL and NIOSH ATFs ($IPIL_{EARCAL} – IPIL_{NIOSH}$). The average IPIL differences 1.4 dB at the 132 dB level, 1.8 dB at the 150 dB level, and 1.4 dB at the 168 dB level. The average IPIL differences between the two fixtures were statistically significant for all three impulse levels ($p < 0.05$).

3M™ Peltor™ TacticalPro Communications Headset

The IPIL data for the TacticalPro earmuff are presented in Table 3 and illustrated in Figure 5. Seven of the ten low-level impulses were above the allowable 134 dB limit, but none exceeded 135.3 dB. The impulses generated for the 150 dB and 168 dB levels were all within the acceptable range.

Comparison of the right and left ear IPIL values for the E-A-RCAL ATF yielded average differences of 1.6 dB for the 132 dB impulses, 1.1 dB for the 150 dB impulses and 2.9 dB for the 168 dB impulses. For all three impulse levels, the IPIL differences were statistically significant using the Student's t-test ($p < 0.05$) and the left ear exhibited more IPIL than the right ear.

The average IPIL differences between the left and right ears ($IPIL_{Left} – IPIL_{Right}$) of the NIOSH ATF were -1.1 dB for the 132 dB impulses, -1.2 dB for the 150 dB impulses and 0.3 dB for the 168 dB impulses. These IPIL differences were statistically significant at the 132 dB impulse level ($p < 0.05$).

The average IPIL estimates were compared between the E-A-RCAL and NIOSH ATFs ($IPIL_{EARCAL} – IPIL_{NIOSH}$). The average IPIL differences 0.7 dB at the 132 dB level, 1.4 dB at the 150 dB level, and 0.6 dB at the 168 dB level. The average IPIL differences between the two fixtures were statistically significant for all three impulse levels ($p < 0.05$).

Dual protection ETYPlugs Earplug and TacticalPro Earmuff

The IPIL estimates for the dual protection combination are given in Table 4 and illustrated in Figure 6. Nine of the ten low-level impulses were outside the acceptable range of 130-134 dB but did not exceed 135.4 dB. However, for the middle and higher impulse levels, all of the impulses were within the acceptable range of 148-152 dB and 166-170 dB.

For the E-A-RCAL ATF, the average differences between left and right ears were 1.9 dB for the 132 dB impulses, 2.4 dB for the 150 dB impulses and 3.1 dB for the 168 dB impulses. For all impulse levels, the IPIL differences were statistically significant using the Student's t-test ($p < 0.05$) and the left ear exhibited more IPIL than the right ear.

The average IPIL differences between the left and right ears ($IPIL_{Left} – IPIL_{Right}$) of the NIOSH ATF were -0.9 dB for the 132 dB impulses, 0.3 dB for the 150 dB impulses and -1.1 dB for the 168 dB impulses. These IPIL differences were statistically significant at the 132-dB impulse level ($p < 0.05$).

The average IPIL estimates were compared between the E-A-RCAL and NIOSH ATFs ($IPIL_{EARCAL} – IPIL_{NIOSH}$). The average IPIL differences 0.9 dB at the 132 dB level, 2.5 dB at the 150 dB level, and 1.7 dB at the 168 dB level. The average IPIL differences between the two fixtures were statistically significant for all three impulse levels ($p < 0.05$).

Change in IPIL with Impulse Level

The average peak impulse level, the means and standard deviations of the IPILs from the E-A-RCAL and NIOSH ATFs, and the average difference in IPIL for the two fixtures are summarized in Table 5. The differences between fixtures were discussed at the end of each of the sections for the various protectors. Generally, the IPILs measured with the E-A-RCAL ATF were greater than those measured with the NIOSH ATF. If the impulse levels were different at the locations of the fixtures' ears, then differences in the IPILs would be expected.

The IPIL values increase with level and therefore a linear regression was fit using MATLAB to the IPIL data from each fixture as a function of level. Table 6 displays the slopes and intercepts for the fits to the IPIL data along with the confidence intervals for each parameter. The linear fit approximates the change in IPIL and is useful only in the region 134 to 168 dB. Other functions can be used to fit the behavior; however, given the limited number of test levels, a linear model was deemed sufficient for the data from this study. As seen in Table 6, the IPIL slope measured with each fixture was within the confidence interval of the other fixture's slope, for the Combat Arms earplug, TacticalPro earmuff, and dual protector combination. The slope for the IPIL change with level for the ETYPlugs earplug had confidence intervals that overlapped between fixtures, but the estimates from each fixture did not fall within the confidence interval of the other fixture.

Comparison of NIOSH MATLAB and VIAcoustics IPILA Methods

Table 7 summarizes a comparison between two data analysis programs for computing IPIL, using data recorded by the NIOSH system from the E-A-RCAL ATF. NIOSH has developed a series of MATLAB routines implementing the IPIL calculations detailed by the ANSI/ASA S12.42-2010 standard. VIAcoustics has developed the IPILA analysis software that also implements the ANS S12.42-2010 standard. One purpose of conducting this experiment was to compare the results determined with the MATLAB software and with the IPILA software. Table 7 displays the results when the 1-second impulse waveforms recorded by the NIOSH Sound Power VI have been analyzed with both pieces of software. The means and standard deviations are identical to one-tenth of a decibel. In fact, the individual IPIL values agreed to within 0.01 dB. When the impulses were windowed to shorter signal duration (105 ms), some discrepancies between implementations were identified. Further research is required to determine the cause of these differences. The results presented herein were obtained by analyzing the full 1-second impulse signals.

Bone-Conduction Corrections

Using the bone-conduction correction described in ANSI/ASA S12.42-2010, the 41 dB limit at 2000 Hz was applied to all of the IPIL values according to Equation (9). Table 8 reports both the uncorrected, corrected, and differences between the two estimates of IPIL measured with both the NIOSH and E-A-RCAL ATFs. For IPIL values greater than 32 dB, the correction will be more than 0.5 dB. As the uncorrected IPIL values increase, the bone-conduction corrected IPIL reaches an asymptote of 41 dB. Once the uncorrected value exceeds 50 dB, the bone-conduction corrected IPIL value will be within 0.5 dB of 41 dB. Testing for significant differences in the IPIL values after correction could be done, but observed differences would be diminished significantly because the correction leads to an asymptotic result. Since this report is concerned primarily with the reproducibility of measurements between the two fixtures, the uncorrected IPIL values are of more importance.

Discussion

Interpretation of IPIL Differences

Significant differences were observed in the measurements of the IPIL between the left and right ears of the E-A-RCAL ATFs for the four protection conditions and three impulse levels (See Table 7). The left ear of the E-A-RCAL ATF always measured higher IPIL compared to the right ear for all four protectors across the three impulse levels (See Tables 1-4). However, the IPIL measurements for the NIOSH ATF did not display similar trends compared to the E-A-RCAL ATF. Even though these two ATFs were nearly identical in their overall design, statistically significant differences were observed for both right and left ears in the same fixture and between the two ATFs. These sources of the differences between right and left ears and between fixtures must be more carefully researched. Potential sources contributing to these differences are discussed below.

Transfer Functions

The ANSI/ASA S12.42-2010 standard states that the transfer functions between the field microphone and the open ear microphones of the ATF are to be measured at the 132 and 150 dB impulse levels. At the 168 dB impulse range, the standard notes that the ATF microphones in unprotected ears could exceed the typical maximum level of about 174 dB for a 1/4" condenser microphone. The open ear canal and the acoustic impedance of the ear simulator combine to provide gain to the impulse. Thus, if the gain of the transfer function of the open ear (TFOE) exceeds 6 dB, the impulse at the ear simulator would exceed 174 dB for a 168 dB free-field impulse. The technical specifications for the GRAS 40BP cartridge identify an upper limit of 181 dB for a 120V (±60V) power supply depending upon the preamplifier used with the cartridge.

During the field study at E-A-RCAL (and other field studies), the open-ear responses were measured for 168 dB impulses, in addition to the 150 and 132 dB impulses. For the 132 and 150 dB TFOE responses, gains of about 4 to 8 dB were observed. At the 168 dB level, the gain due to the TFOE was increased to about 8 to 12 dB. In particular, the left ear of the E-A-RCAL fixture consistently yielded around 12 dB of gain, whereas the right ear yielded about 9 dB, for 168 dB impulses. The NIOSH ATF consistently yielded an 8 dB gain. Thus, the open-ear peak response for the E-A-RCAL fixture was 4 to 6 dB above the maximum limit of the condenser microphone. The excessive pressure could yield a distortion of the impulse measured from the microphone.

The impulses measured in this study did not exhibit any obvious distortion. Therefore, TFOEs were computed for all three test levels. The IPIL analysis at each level used the TFOE computed for that level, without reuse of the 150 dB TFOE for the 168 dB test level. Additionally, throughout the study, care was exercised to maintain the position of the ATFs and blast probe to prevent the need to reassess the TFOE.

Earcanal Length

The NIOSH ATF was first one constructed by ISL after the ANSI/ASA S12.42-2010 standard was published and was designed to conform to the standard's requirements. The ANSI/ASA S12.42-2010 standard stipulates that the earcanal extension added to the coupler shall be 14±1 mm in length. The NIOSH ATF earcanal extensions permitted earplug insertions of about 13.5 mm. Since the issue of the earcanal length was discussed with the designers, subsequent ISL ATFs (including E-A-RCAL's) were built with earcanal extensions that permitted about 16 mm of earplug insertion depth.

Slightly longer earcanal extensions should yield higher IPIL estimates because more of the lateral surface of the earplug would be in contact with the walls of the earcanal extension. Although this study did not evaluate a foam earplug, impulse data collected by NIOSH at the US Army Aeromedical Research Laboratories at Fort Rucker indicates that the IPIL will vary 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, it will be critical to providing protection from impulse noise.

In this study, only premolded, triple-flanged earplugs were evaluated. The third flange (most lateral) made contact with the earcanal extension. This flange was larger than the diameter of the earcanal extension; therefore, the flange would wrinkle if it were inserted further into the canal. During testing, the plugs were inserted such that the third flange just made contact with the earcanal extension and was not wrinkled. Flanged earplugs fitted into a shorter earcanal do not contact with the lateral end of the earcanal (Murphy, 2003; Murphy et al., 2012).

As shown in Table 5, the average differences between the NIOSH and E-A-RCAL fixtures were approximately 1.5±0.5 dB for the Combat Arms earplug, 1.6±0.4 dB for the ETYPlugs earplug, 0.7±0.7 dB for the TacticalPro earmuff, and 1.7±0.9 dB for the dual-protection ETYPlugs earplug and TacticalPro earmuff. From Table 8, nearly all of these conditions were statistically significant.

Fixture Position

The differences that were observed between the NIOSH and E-A-RCAL fixtures could have resulted from positioning relative to the impulse wave front. The fixture position was determined by extending a tape measure from the center of the face of the catenoidal horn to the right and left ear of each ATF. The rotational orientation was achieved by visually sighting along the seam of each fixture to align with the center of the mouth of the horn. If one head were slightly turned, the impulse source might produce an acoustic shadow on the side of the head facing away from the source, which might account for differences between the two ears of a fixture.

The impulse wave front expands as it propagates from the shock tube pressure chamber to the mouth of the horn. Once radiated from the horn, the impulse produces a non-uniform acoustic field, in which the test fixtures and free-field microphones are located. A recent study investigated the acoustic field produced by the shock tube and catenoidal horn in the NIOSH Impulse Noise Laboratory, which are of the same design as the system used in the E-A-RCAL Laboratory. The radiated impulses were found to be directional, with locations along the major axis of the horn having the highest peak sound pressure levels for a given impulse. At a distance of approximately 1 meter (39.4 inches) from the mouth of the horn, the peak level decreased by about 4 dB from the central axis to a position approximately 0.5 m (23.6 in) to either side. Moving along the central axis, from directly in front of the mouth of the horn to a position approximately 2.3 m (90.6 in) away, the peak level decreased approximately 9 dB.

In the present study, the E-A-RCAL fixture was located seven centimeters closer to the mouth of the horn than the NIOSH fixture. The unoccluded peak pressures were compared for each ear of the fixtures and the level at the left and right ears of the E-A-RCAL fixture were 3 and 0.6 dB greater than the unoccluded left and right ear microphones of the NIOSH fixture for the 170 dB impulses. Similar trends were observed for the other test levels: the IPIL measured in both ears of the E-A-RCAL fixture was always higher than the NIOSH fixture. This suggests that the field was more intense at the E-A-RCAL fixture than at the NIOSH fixture. A 3 dB increase in the peak pressure level at the ear of the E-A-RCAL fixture would amount to an approximately 1.5 dB increase in the IPIL values. Additionally, almost every IPIL estimate for the left ear of the E-A-RCAL fixture was greater than that for the right ear. This effect may be evidence of an acoustic shadow. For the NIOSH ATF, the differences between ears were not so pronounced, but generally the same trend was observed: the ear closest to the horn's axis had a lower IPIL than the ear that was furthest from the axis. However, given the previously discussed directivity of the shock tube and horn system, the ears of the ATFs furthest from the horn axis should be receiving a lower impulse level, which should lead to a lower IPIL than the ears closest to the horn axis.

Computational Method

Murphy et al. (2012) consider the influence of several factors on IPIL values: DC offset of background noise, time alignment of impulse peaks, tapered sample windows, and analysis time window length. DC offset was observed to have an effect of no more than 0.2 dB on the IPIL estimates. The alignment of the impulse peaks had a similar effect of about 0.2 dB. However, alignment had a greater effect for the low-level impulse than for the high-level impulses. A time window with 1 ms cosine-squared onset and offset was used to evaluate whether tapering at the beginning and the end of the sample affected the IPIL estimates. Tapering had a negligible effect, less than 0.01 dB. The pre-trigger interval was varied between 100 and 500 samples (1 and 5 ms at a 100 kHz sampling rate). The pre-trigger interval exhibited an effect of about ± 0.1 dB for the low-level impulses and a negligible effect for the high-level impulses. Finally, the duration of a time window containing the portion of the impulse used for analysis exhibited significant effects.

In the analysis of the EARCAL data, we have not investigated such a multitude of signal processing details. The average amplitude of the background noise from the pre-trigger interval was subtracted from the amplitude of the entire waveform. The impulses were not time aligned in the MATLAB code analysis of the entire 1-second waveform. When the impulses were windowed to 105 ms, the impulses were time aligned. Tapering was not applied, and a pre-trigger interval of 5120 samples (5 ms) was used. The average results from the MATLAB analysis did not differ by more than 1 dB between the windowed and unwindowed impulses.

Interpretation of the Results

Single versus Double Protection

In continuous noise, Berger (1983) investigated the effects on real ear attenuation at threshold for single and double hearing protection. He proposed an algebraic summation of the attenuation for the individual protectors' performance at each frequency band and limited the maximum attenuation using the bone-conduction flanking pathway. Abel and Armstrong (1992) conducted a comparison study of two earplugs and two earmuffs in both single and dual combinations. Their analysis demonstrated that Berger's formula reasonably predicted the combined attenuation and overestimated the attenuation by about 1 or 2 dB. The effects of dual protection when worn in impulse noise should be quite similar to the continuous noise case. Generally, the hearing conservation community adds about 6 dB to the Noise Reduction Rating for the earplug to estimate the benefit from wearing double protection.

Studies similar to Berger (1983) and Abel and Armstrong (1992) have not been performed for impulse noise because ATFs meeting the ANSI/ASA S12.42-2010 performance requirements were not previously available. Murphy and Tubbs (2007) reported peak reduction for a combination of the 3M™ E-A-R™ Classic™ foam earplug and the David Clark Model 27 earmuff. Individually, the two protectors provided about 30 dB of peak reduction ($L_{peak} – L_{protected\ peak}$). The combined peak reduction was observed to be about 55 dB and approached the sum of the individual peak reductions for the protectors. If the fixture has a maximum isolation of 60 or 70 decibels, then the levels observed will be limited according to the maximum isolation. Between 63 Hz and 10 kHz, the isolation of the NIOSH ISL fixture was greater than 60 dB and was 70 dB at most frequencies (Buck and deMezzo, 2008).

In the present study, the ETYPlugs earplug and TacticalPro earmuff were tested in combination. The average IPIL values for the protectors are given in Table 5. At the 132 dB impulse level, the average IPILs for the ETYPlugs earplug were 15.3 and 14.0 dB measured in the E-A-RCAL and NIOSH ATFs, respectively. For the same level, the IPILs were 22.7 and 22.1 dB for the TacticalPro earmuff. For the dual-protector condition, the average IPILs were 30.8 and 30.0 dB, approximately 6 to 8 dB less than the summation of the IPILs measured in isolation. A similar comparison for the IPILs measured at 150 dB yielded approximately 10 to 11 dB less IPIL for the dual-protector condition than the sum of the individual protectors. At the 168 dB impulse level, the difference between the sums of the individual IPILs and the dual protection was approximately 20 to 21 dB. The dual protection IPILs increase at a slower rate than those of the individual protectors.

Conclusions

We observed significant differences in the measurement of IPIL between the two ears of the E-A-RCAL ATF and between the two ATFs tested in this study. These differences suggest that the IPIL is sensitive to small changes in measurement conditions for the fixtures and in impulse levels. Thus, IPIL measurement will present new challenges for comparing repeatability within a laboratory and reproducibility among multiple laboratories.

For all of the protectors evaluated in this study, the IPIL increased with increasing impulse level. For the Combat Arms earplug in the open-valve condition, the change in IPIL was much greater than for the other protectors. Because this earplug has a valve that provides little or no attenuation at low levels but substantially more at higher levels, its performance was consistent with its design.

One of the more valuable results from this study was the comparison of two implementations of the ANSI/ASA S12.42-2010 computations for estimating the IPIL. Although the equations can be written in just a few lines, the process of implementing them in computer code is tedious and requires attention to the signal processing details. NIOSH developed its Sound Power VI LabView software to collect the data and the analysis routines were developed in MATLAB. VIAcoustics extended their LabView data acquisition program, Trident, to support the impulse noise measurement. Trident is tightly coupled with the IPILA software to provide essentially a turnkey solution for measuring the IPIL of a hearing protector. Agreement between the two systems was assessed through a concerted effort to develop code that allowed the NIOSH MATLAB data files to be translated into the Trident WAV files that are read by IPILA. The two systems agreed to within 0.01 decibels when analyzing the full 1-second recordings collected by the NIOSH data acquisition system. IPILA and MATLAB have the ability to select a windowed segment of the impulse for analysis. When that option was exercised, the two systems did not exhibit such close agreement. The differences between the two analysis packages could be as much as 3 or 4 dB. This issue has been discussed with VIAcoustics and we are working to resolve the differences.

This research study focused on measurement techniques to compare acoustic test fixture performance with different hearing protectors and a single impulse source. The effect of the impulse spectrum on hearing protector attenuation as a function of frequency still lacks a firm theoretical basis. Nonlinear acoustics, leaks in the seal of a protector, and material properties all make impulse attenuation difficult to predict. With data collected from multiple impulse sources, acoustic models can be developed for the response of a hearing protector to an arbitrary impulse noise source.

Recommendations

The two fixtures had minor differences in ear canal length, and the effect of this length on protector performance should be further investigated. Such an investigation will help determine if there is any correlation between the ear canal length and assessment of IPIL. It would not be expected that the protectors, which were premolded flanged earplugs or earmuffs, would exhibit significant differences based on insertion depth. Analysis of a foam earplug in a NIOSH investigation at Fort Rucker, however, confirmed that increased insertion depth yielded a higher IPIL.

Statistically significant differences were observed in the measurements of the IPIL between the left and right ears of the E-A-RCAL ATF but not between the left and right ears of the NIOSH ATF. These IPIL differences could be attributed to systematic positioning effects. A second study switching the positions of the ATFs on either side of the blast probe could provide a better understanding of the source of the differences.

Future comparisons of fixtures of similar make and manufacture should use a control protector that does not exhibit significant level-dependent effects. For instance, the E-A-R Classic foam earplug is considered to provide a uniform level of attenuation, regardless of level. If the earplug is inserted to the same extent in each fixture’s ear canal, then the effect of ear canal length will be reduced. Repeated evaluations of the control earplug and/or earmuff would help ensure consistent results from impulse generation across a range of tests. Although the time for measurements was limited during this study, future measurements should include more calibration shots before and after a device is tested. These additional shots could help identify any shift occurring in the fixtures during the fitting and removal of protectors.

Further work needs to be conducted to resolve possible differences in the computation of the IPIL value. Currently, three or four laboratories in the United States are using the Trident measurement system and the IPILA software. Although the developers of the IPILA and NIOSH computation libraries worked from the same set of equations in the ANSI/ASA S12.42-2010 standard, the answers do not agree to within a few tenths of a decibel, the typical tolerance for an accurate acoustic measurement and computation.

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Tables

Table 1: 3M™ E-A-R™ Single-Ended Combat Arms™ Earplug (with valve open) IPIL data without bone-conduction correction.

	E-A-RCAL ATF			NIOSH ATF		
Peak level (dB)	Average IPIL	Left Ear IPIL	Right Ear IPIL	Average IPIL	Left Ear IPIL	Right Ear IPIL
133.98	12.77	13.64	11.90	10.73	10.29	11.16
132.67	10.94	11.69	10.20	7.74	7.93	7.55
135.02	11.33	12.27	10.39	10.04	10.02	10.06
134.67	12.98	13.93	12.02	11.11	11.40	10.82
133.82	11.86	12.58	11.14	9.87	9.73	10.01
135.05	12.15	13.42	10.89	10.56	10.50	10.61
136.38	12.30	12.97	11.63	10.54	10.20	10.89
135.12	12.09	12.38	11.80	11.86	11.36	12.36
131.38	9.41	9.69	9.13	7.45	6.87	8.02
134.82	12.18	12.89	11.48	9.58	9.69	9.48
149.06	21.66	22.68	20.63	20.56	20.85	20.28
150.90	22.93	23.85	22.00	21.33	21.10	21.56
149.58	22.08	22.87	21.28	20.70	21.06	20.34
150.37	22.52	23.42	21.61	21.76	21.78	21.74
151.08	24.14	25.10	23.19	22.59	22.27	22.90
150.48	23.13	24.65	21.62	21.40	21.04	21.75
148.65	20.62	21.41	19.83	20.11	20.10	20.12
150.65	20.37	21.14	19.61	19.18	18.72	19.63
149.74	21.20	22.49	19.91	20.36	20.18	20.54
148.71	21.03	22.12	19.94	19.90	19.90	19.90
168.17	35.91	37.64	34.18	34.90	35.13	34.66
168.15	35.39	37.42	33.36	34.77	35.45	34.08
168.02	36.16	37.97	34.35	34.80	35.45	34.15
167.43	35.89	37.63	34.16	34.49	34.93	34.05
168.06	35.80	37.50	34.11	34.32	34.41	34.23
167.90	36.24	37.98	34.50	34.31	34.59	34.03
168.17	35.76	36.95	34.57	34.46	34.64	34.28
167.94	35.35	36.85	33.84	34.50	34.91	34.10
167.80	35.59	36.58	34.59	34.72	34.90	34.55
167.76	35.85	37.14	34.55	34.19	34.91	33.47

Table 2: Etymotic Research ETYPlugs® Earplug IPIL data without bone-conduction correction.

	E-A-RCAL ATF			NIOSH ATF		
Peak level (dB)	Average IPIL	Left Ear IPIL	Right Ear IPIL	Average IPIL	Left Ear IPIL	Right Ear IPIL
132.25	14.65	15.67	13.64	12.71	11.70	13.71
132.94	16.39	17.97	14.82	13.77	13.99	13.55
133.85	14.32	15.31	13.33	11.90	11.09	12.71
132.53	14.86	15.33	14.40	12.79	12.28	13.31
134.23	13.88	14.65	13.12	12.72	12.36	13.08
134.65	13.71	14.75	12.68	13.30	12.02	14.57
135.03	14.97	14.59	15.34	15.30	14.34	16.26
134.43	14.67	14.36	14.98	13.89	13.10	14.68
134.35	17.24	17.97	16.52	15.36	15.71	15.01
134.56	17.93	18.36	17.50	16.56	17.09	16.03
149.93	20.58	21.62	19.54	18.82	18.77	18.88
148.54	18.86	19.74	17.99	16.97	16.81	17.13
147.97	19.50	20.48	18.51	16.95	16.77	17.12
148.00	17.46	18.67	16.24	15.16	14.67	15.64
149.18	20.33	21.14	19.51	17.89	17.13	18.64
150.74	17.93	18.80	17.05	16.05	15.41	16.69
150.02	19.99	20.51	19.47	18.78	18.44	19.12
148.75	19.42	19.77	19.06	17.96	17.55	18.38
149.08	20.57	21.38	19.77	18.87	18.98	18.76
149.00	20.66	21.55	19.78	19.49	19.96	19.03
168.33	29.84	30.74	28.94	27.14	27.47	26.80
168.09	29.73	30.50	28.96	27.37	27.64	27.11
168.42	28.63	29.24	28.03	26.78	27.17	26.40
167.79	29.10	29.46	28.73	27.00	27.15	26.84
168.11	28.06	28.91	27.21	27.03	26.71	27.34
168.32	28.45	29.47	27.44	27.14	26.94	27.34
167.76	28.56	28.49	28.64	28.30	28.07	28.52
167.87	28.70	28.79	28.62	28.10	27.96	28.24
168.17	29.45	30.06	28.83	28.38	28.88	27.88
168.33	29.39	29.70	29.07	28.21	28.90	27.52

Table 3: 3M™ Peltor™ TacticalPro Communications Headset (with electronics set to unity gain) IPIL data without bone-conduction correction.

	E-A-RCAL ATF			NIOSH ATF		
Peak level (dB)	Average IPIL	Left Ear IPIL	Right Ear IPIL	Average IPIL	Left Ear IPIL	Right Ear IPIL
133.29	22.76	23.93	21.59	21.44	20.89	21.99
134.48	24.36	26.01	22.71	24.01	24.12	23.90
134.34	23.80	25.32	22.28	22.29	20.72	23.86
135.41	21.55	22.27	20.84	22.10	21.08	23.12
135.83	23.41	23.11	23.72	24.06	23.39	24.72
133.93	22.23	22.63	21.82	21.64	21.07	22.21
135.63	24.32	24.99	23.66	22.83	21.89	23.78
134.78	21.39	21.95	20.83	20.08	19.97	20.19
135.80	22.27	23.17	21.36	21.08	20.88	21.28
133.62	20.61	21.10	20.12	20.23	20.26	20.21
149.05	30.02	31.45	28.59	28.51	28.61	28.40
151.92	29.36	29.55	29.18	28.07	26.19	29.95
150.09	30.10	30.88	29.32	28.10	27.36	28.83
149.58	29.43	30.45	28.41	27.78	27.20	28.35
149.47	27.59	28.48	26.71	27.06	27.03	27.09
149.10	27.84	27.57	28.11	27.67	27.86	27.48
148.88	29.32	29.81	28.83	27.59	27.18	28.00
149.41	28.22	28.11	28.33	24.09	20.90	27.28
149.61	28.72	29.03	28.41	28.64	28.99	28.30
149.91	29.33	29.89	28.77	28.04	28.44	27.65
168.15	37.86	39.79	35.92	37.76	37.97	37.54
168.18	37.66	39.53	35.79	37.40	37.15	37.65
168.53	38.07	39.44	36.69	36.84	36.90	36.78
167.86	38.07	39.49	36.64	37.23	37.01	37.44
168.24	37.81	38.98	36.63	37.24	37.43	37.05
167.78	37.51	38.17	36.86	37.37	37.46	37.29
168.14	37.73	39.59	35.86	37.45	37.19	37.72
168.08	38.09	39.81	36.38	37.11	36.68	37.54
168.32	37.84	39.19	36.49	36.68	37.33	36.03
168.25	37.53	38.68	36.38	37.13	37.53	36.73

Table 4: Dual protection Etymotic Research ETYPlugs® Earplug and 3M™ Peltor™ TacticalPro Communications Headset IPIL data without bone-conduction correction.

	E-A-RCAL ATF			NIOSH ATF		
Peak level (dB)	Average IPIL	Left Ear IPIL	Right Ear IPIL	Average IPIL	Left Ear IPIL	Right Ear IPIL
134.74	30.68	32.40	28.96	29.67	29.74	29.61
134.63	31.42	32.67	30.17	30.34	30.10	30.58
135.02	29.26	31.22	27.29	29.08	28.41	29.75
134.87	30.26	32.30	28.22	28.74	28.22	29.26
134.53	31.14	31.80	30.48	29.83	29.24	30.43
133.92	30.53	31.10	29.96	30.02	28.99	31.05
135.31	32.15	32.13	32.17	30.45	29.62	31.27
134.16	30.83	31.09	30.57	29.58	28.48	30.69
134.22	31.02	31.62	30.42	29.84	30.51	29.17
134.27	31.23	31.91	30.55	31.52	31.13	31.91
149.57	39.71	42.13	37.29	35.12	35.73	34.51
149.09	38.23	40.42	36.05	34.71	35.21	34.21
148.91	37.68	39.01	36.35	33.86	33.38	34.33
150.32	38.55	39.98	37.12	34.26	35.38	33.14
149.37	36.09	36.32	35.85	34.58	34.35	34.82
149.73	37.39	38.76	36.03	35.96	35.79	36.12
150.05	38.02	38.80	37.23	35.99	34.82	37.15
150.41	37.26	38.26	36.25	36.12	35.27	36.96
149.33	37.83	38.27	37.40	36.11	37.49	34.74
149.84	39.19	39.90	38.49	37.97	38.54	37.39
168.30	47.52	50.17	44.87	45.00	45.49	44.51
167.99	47.60	50.21	44.99	44.39	44.41	44.38
167.78	46.58	48.74	44.41	43.55	42.16	44.93
168.31	46.14	48.01	44.28	43.77	42.72	44.82
167.76	45.47	47.10	43.85	44.51	43.57	45.44
168.42	45.37	46.00	44.74	44.03	43.20	44.87
168.35	46.21	46.65	45.76	44.89	43.60	46.19
168.14	45.55	46.54	44.57	45.16	44.08	46.25
168.23	46.78	47.82	45.74	45.28	45.77	44.78
168.48	45.86	47.56	44.16	45.73	46.00	45.46

Table 5: Average IPIL and difference between IPIL measured for E-A-RCAL and NIOSH ATFs using MATLAB.

Protector	Peak Level (dB)	E-A-RCAL ATF Avg IPIL ± StDev	NIOSH ATF Avg IPIL ± StDev	Avg Difference E-A-RCAL - NIOSH
Combat Arms Earplug	134.3	11.8 ± 0.6	9.9 ± 1.1	1.9
	149.9	22.0 ± 1.2	20.8 ± 0.9	1.2
	167.9	35.8 ± 0.2	34.5 ± 0.2	1.2
ETYPlugs Earplug	133.9	15.3 ± 1.4	13.8 ± 1.4	1.4
	149.1	19.5 ± 0.8	17.7 ± 1.2	1.8
	168.1	29.0 ± 0.6	27.5 ± 0.7	1.4
TacticalPro Earmuff	134.7	22.7 ± 0.8	22.0 ± 0.9	0.7
	149.7	29.0 ± 0.8	27.6 ± 1.0	1.4
	168.2	37.8 ± 0.2	37.2 ± 0.3	0.6
Dual Protection: ETYPlugs & TacticalPro	134.6	30.9 ± 0.7	29.9 ± 0.6	0.9
	149.7	38.0 ± 0.9	35.5 ± 1.1	2.5
	168.2	46.3 ± 0.8	44.6 ± 0.7	1.7

Table 6: Slopes and intercepts for the change in IPIL with level. Confidence interval for each parameter indicated in parentheses.

Protector	E-A-RCAL ATF		NIOSH ATF	
	Slope ∆dB/dB	Intercept (dB)	Slope ∆dB/dB	Intercept (dB)
Combat Arms Earplug	0.70 (0.68, 0.72)	-84.0 (-87.3, -80.7)	0.74 (0.71, 0.75)	-88.5 (-90.9, -86.0)
ETYPlugs Earplug	0.39 (0.36, 0.41)	-37.2 (-41.7, -32.8)	0.40 (0.37, 0.43)	-41.1 (-45.7, -36.4)
TacticalPro Earmuff	0.43 (0.41, 0.46)	-36.5 (-39.9, -33.1)	0.46 (0.43, 0.48)	-39.7 (-43.0, -36.4)
Dual Protection: ETYPlugs & TacticalPro	0.44 (0.42, 0.47)	-29.1 (-32.9, -25.2)	0.44 (0.41, 0.46)	-29.5 (-33.3, -25.8)

Table 7: Average IPIL computed for E-A-RCAL ATF Using MATLAB and IPILA with the full-length signal.

Protector	Peak Level (dB)	Average IPIL from MATLAB	Average IPIL from IPILA
Combat Arms Earplug	132	11.8 ± 0.6	11.8 ± 0.6
	150	22.0 ± 1.2	22.0 ± 1.2
	168	35.8 ± 0.2	35.8 ± 0.2
ETYPlugs Earplug	132	15.3 ± 1.4	15.3 ± 1.4
	150	19.5 ± 0.8	19.5 ± 0.8
	168	29.0 ± 0.6	29.0 ± 0.6
TacticalPro Earmuff	132	22.7 ± 0.8	22.7 ± 0.8
	150	29.0 ± 0.8	29.0 ± 0.8
	168	37.8 ± 0.2	37.8 ± 0.2
Dual Protection: ETYPlugs & TacticalPro	132	30.9 ± 0.7	30.9 ± 0.7
	150	38.0 ± 0.9	38.0 ± 0.9
	168	46.3 ± 0.8	46.3 ± 0.8

Table 8: Paired *t*-test analysis of IPIL differences between fixtures and between right and left ears of each fixture.

Protector	Peak Level	E-A-RCAL & NIOSH ATFs		E-A-RCAL ATF Right-Left		NIOSH ATF Right-Left	
		Student's *t*	*p* value	Student's *t*	*p* value	Student's *t*	*p* value
Combat Arms Earplug	132	7.52	0	7.90	0	**-1.55**	**0.1548**
	150	9.43	0	13.28	0	**-1.03**	**0.3280**
	168	9.73	0	15.54	0	5.27	0.0005
ETYPlugs Earplug	132	4.83	0.0009	3.29	0.0094	-2.32	0.0453
	150	12.03	0	10.75	0	**-2.13**	**0.062**
	168	5.84	0.0002	4.75	0.001	**1.32**	**0.2182**
TacticalPro Earmuff	132	2.71	0.024	4.3	0.002	-3.29	0.0094
	150	3.94	0.0034	3.19	0.0109	**-1.03**	**0.332**
	168	4.42	0.0017	11.37	0	**0.41**	**0.6891**
Dual Protection: ETYPlugs & TacticalPro	132	4.79	0.001	4.24	0.0022	-2.76	0.0222
	150	5.85	0.0002	5.3	0.0005	**0.49**	**0.6365**
	168	4.98	0.0008	6.37	0.0001	**-2.22**	**0.054**

Note: **Bold numbers** are not statistically significant at ($p < 0.05$).

Table 9: Changes in the IPIL results in decibels (dB) when bone-conduction corrections are applied.

Protector	Peak Level (dB)	E-A-RCAL ATF Uncorrected (dB)	E-A-RCAL ATF Corrected (dB)	E-A-RCAL ATF Difference (dB)	NIOSH ATF Uncorrected (dB)	NIOSH ATF Corrected (dB)	NIOSH ATF Difference (dB)
Combat Arms Earplug	132	11.8	11.8	0.0	9.9	9.9	0.0
	150	22.0	21.9	0.1	20.8	20.8	0.0
	168	35.8	34.7	1.1	34.5	33.6	0.9
ETYPlugs Earplug	132	15.3	15.3	0.0	13.8	13.8	0.0
	150	19.5	19.5	0.0	17.7	17.7	0.0
	168	29.0	28.7	0.3	27.5	27.3	0.2
TacticalPro Earmuff	132	22.7	22.6	0.1	22.0	21.9	0.1
	150	29.0	28.7	0.3	27.6	27.4	0.2
	168	37.8	36.1	1.7	37.2	35.7	1.5
Dual Protection: ETYPlugs & TacticalPro	132	30.9	30.5	0.4	29.9	29.6	0.3
	150	38.0	36.2	1.8	35.5	34.4	1.1
	168	46.3	39.9	6.4	44.6	39.4	5.2

Figures

Figure 1: E-A-RCAL and NIOSH acoustical test fixtures located on the left and right of the blast probe facing the catenoidal horn.

Figure 2: The three models of hearing protectors tested in this field study. The 3M™ E-A-R™ Single-Ended Combat Arms™ Earplug has a toggle that was opened during testing. The Etymotic Research ETYPlugs® Earplug was tested as is. The 3M™ Peltor™ TacticalPro Communications Headset was tested with electronics on and set to unity gain. The double protector combination of the ETYPlugs earplug and TacticalPro earmuff was also tested.

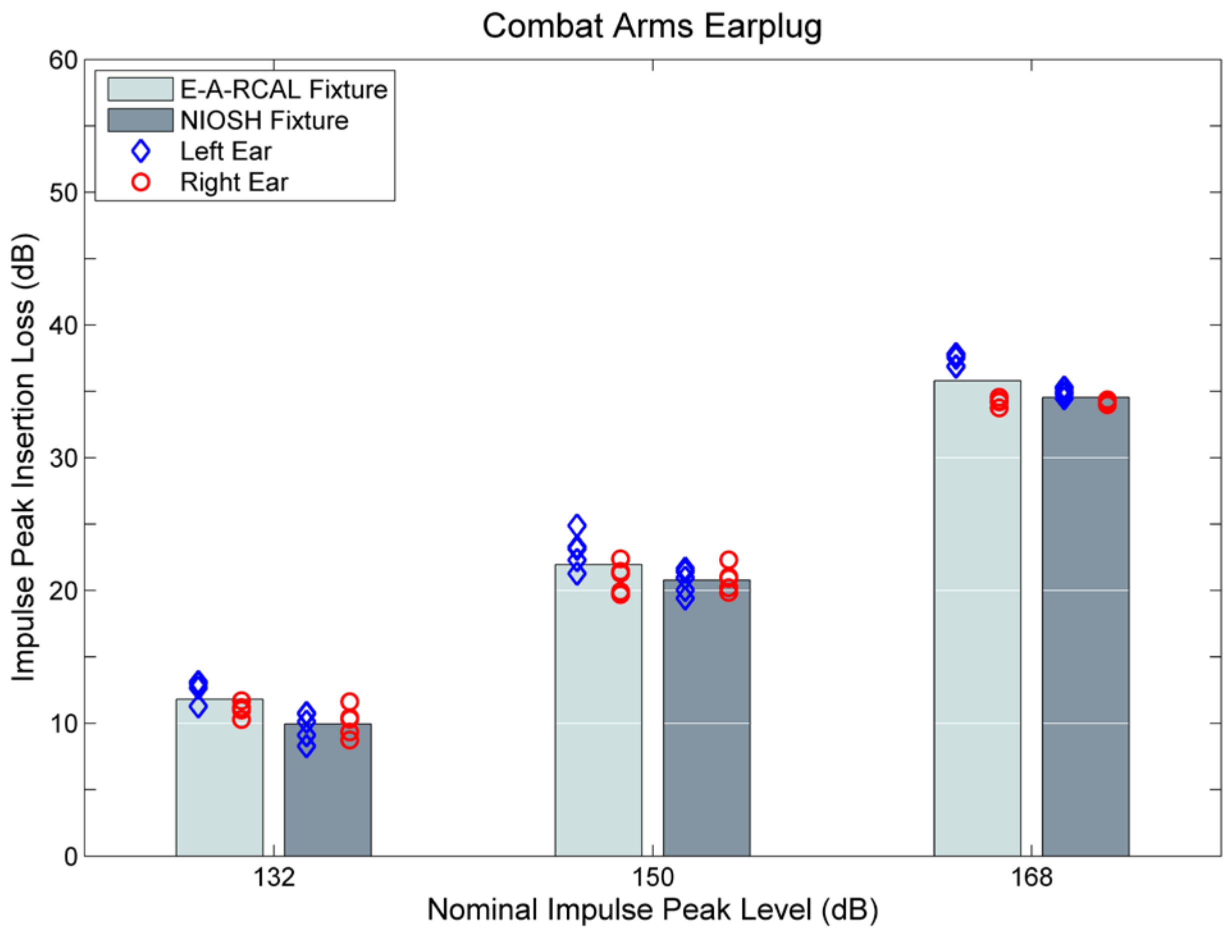

Figure 3: 3M™ E-A-R™ Single-Ended Combat Arms™ Earplug (tested with valve open) IPIL results. The bars correspond to the average IPIL for each test level as measured on each fixture. The diamonds and circles are the average IPIL values for each ear of each sample.

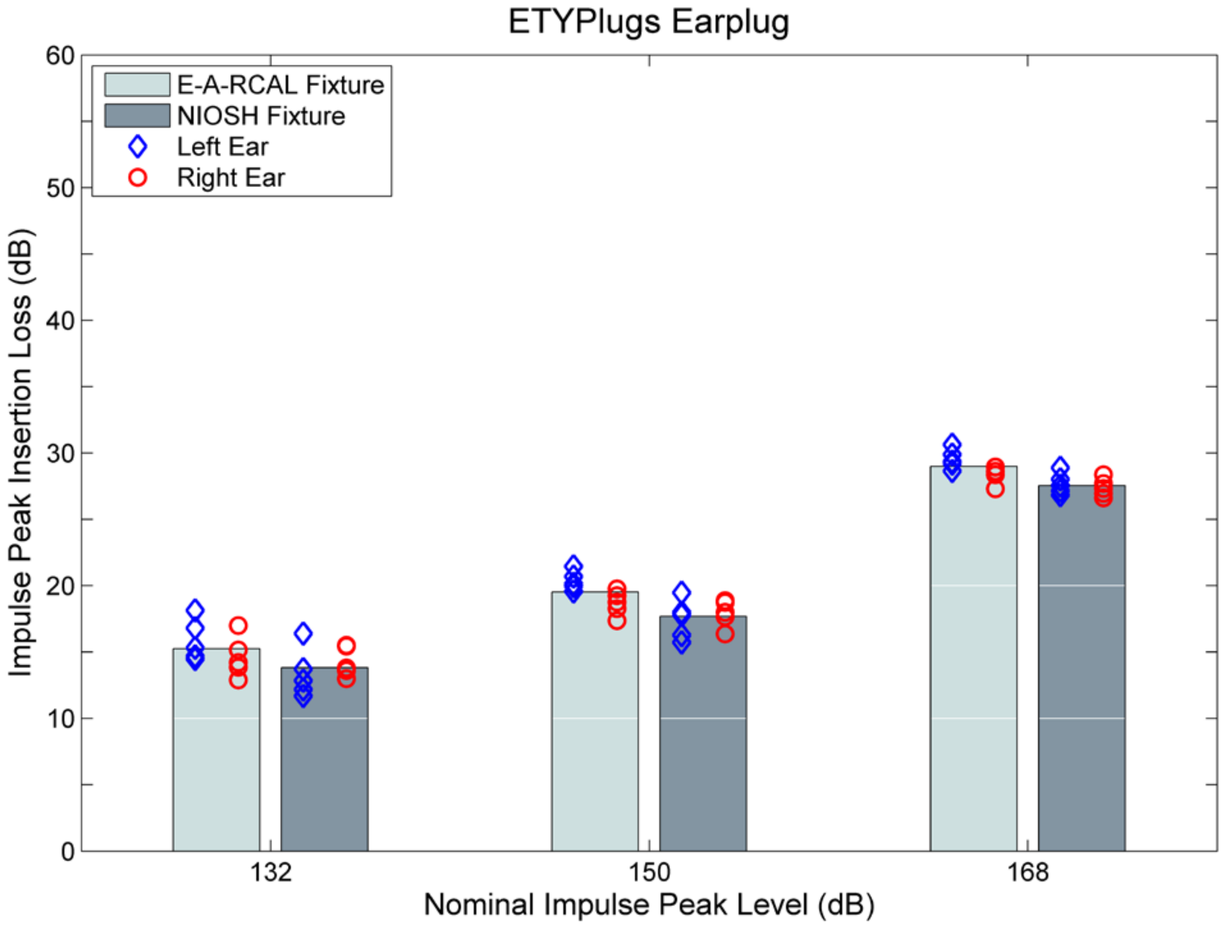

Figure 4: Etymotic Research ETYPlugs® Earplug IPIL results. The bars correspond to the average IPIL for each test level as measured on each fixture. The diamonds and circles are the average IPIL values for each ear of each sample.

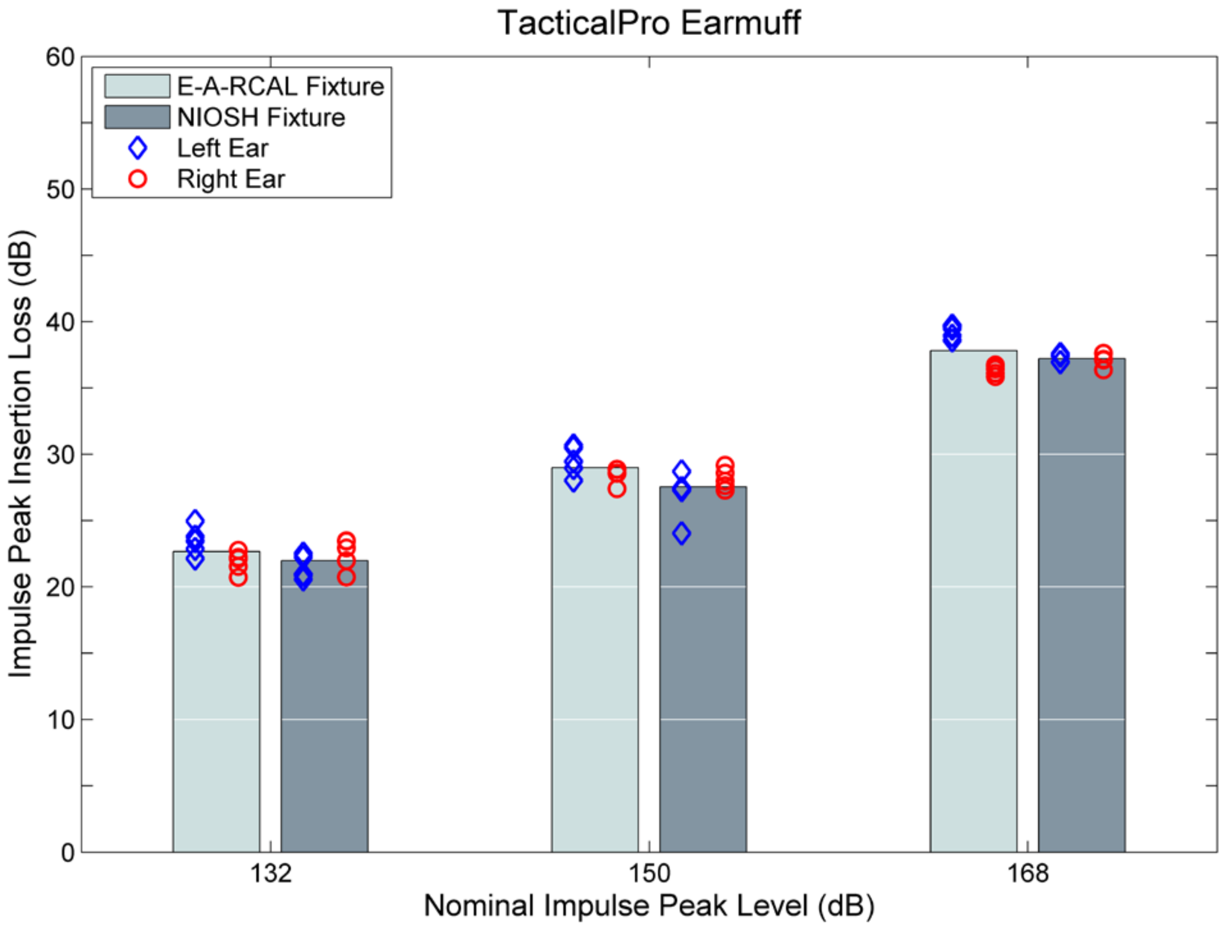

Figure 5: 3M™ Peltor™ TacticalPro Communications Headset (tested with electronics on and set to unity gain) IPIL results. The bars correspond to the average IPIL for each test level as measured on each fixture. The diamonds and circles are the average IPIL values for each ear of each sample.

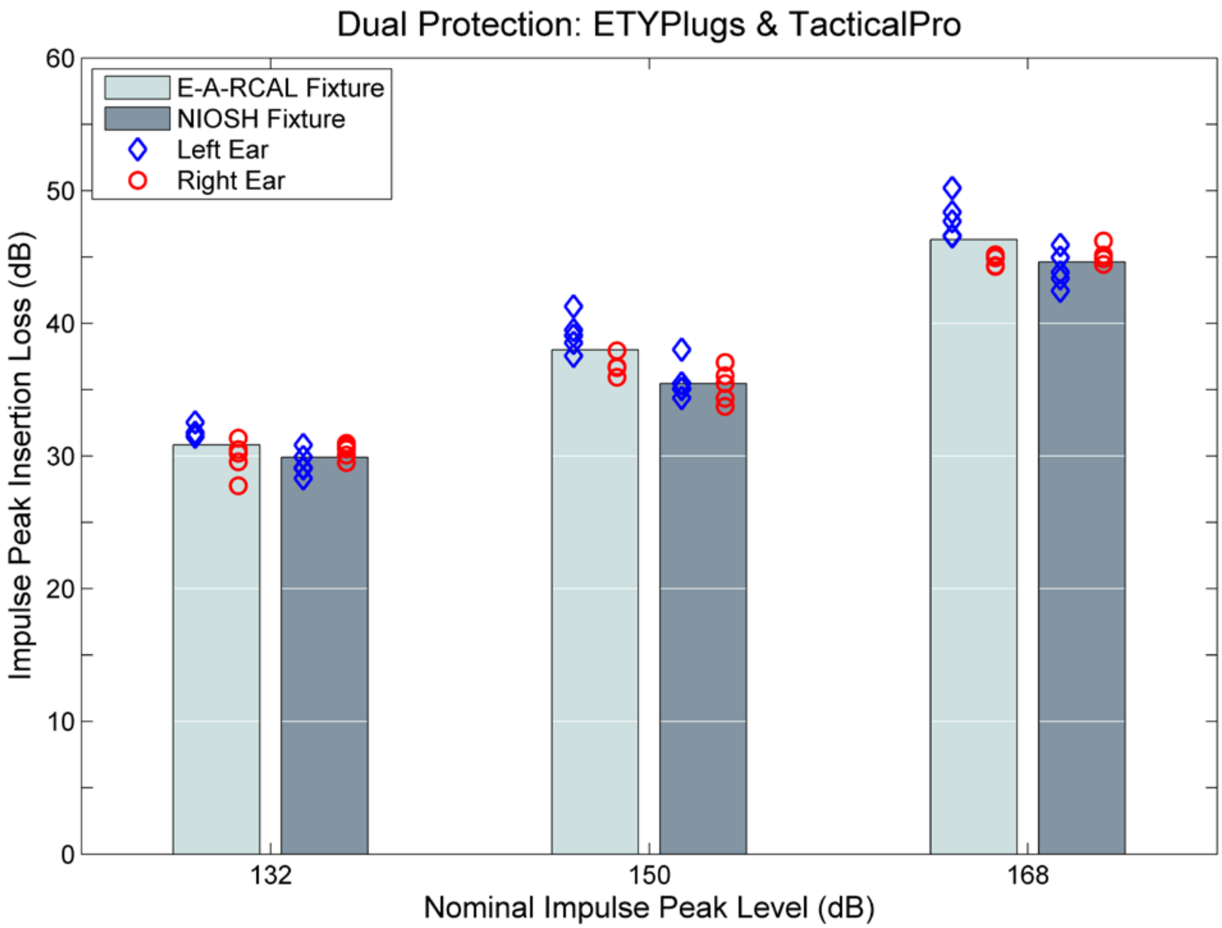

Figure 6: Dual protection Etymotic Research ETYPlugs® Earplug and 3M™ Peltor™ TacticalPro Communications Headset IPIL results. The bars correspond to the average IPIL for each test level as measured on each fixture. The diamonds and circles are the average IPIL values for each ear of each sample.

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