Comparison of different types of hearing protection devices for use during weapons firing

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ABSTRACT

Introduction: Hearing protection devices (HPDs) are not rated for impulse noise, which makes it difficult to select an appropriate device for use during weapons firing. Measurements of different types of HPDs (level independent, level dependent, earplugs, and earmuffs) were performed following American National Standards Institute/Acoustical Society of America S12.42 procedures. **Methods:** A rifle producing a peak level of 154 decibels of sound pressure level was used as the noise source for the measurements. The devices tested were E-A-R Classic earplugs, Combat Arms double-end earplugs, ETY·Plugs earplugs (standard fit), Peltor H10A earmuffs, and Peltor PowerCom Plus earmuffs. The earmuffs were also tested in combination with the E-A-R Classic earplugs and with ballistic glasses. **Results:** The earplug and earmuff combinations provided the most protection, followed by the level-independent earplugs, earmuffs, and level-dependent earplugs. Wearing of ballistic glasses reduced the effectiveness of the earmuffs. **Discussion:** Although the results provide information about the level of protection that is possible for several types of HPDs, the best choice of HPD depends on the operational setting. The combination of level-independent earmuffs and earplugs was the most effective, but it is not a practical solution when communication is required. Earplugs should be worn in cases in which earmuffs interfere with sighting the weapon or are incompatible with other gear such as a helmet or glasses. Future work should include different types of communication headsets and different combinations of HPDs.

Key Words: hearing, hearing protection devices, noise-induced hearing loss, military personnel, noise

RÉSUMÉ

Introduction: Les protecteurs auditifs ne sont pas cotés pour les bruits impulsifs, ce qui rend difficile la sélection de protecteurs auditifs lors de mise à feu d'arme. Les mesures sur les différents types de protecteurs auditifs (de niveau indépendant, de niveau dépendant, bouchons d'oreilles et oreillères) ont été faites en suivant les procédures de la société *American National Standards Institute/Acoustical Society of America (ANSI/ASA) S12.42.* **Méthodes:** Un fusil produisant un bruit maximal de 154 dB SPL a été utilisé comme source de bruit pour l'étude. Les protecteurs étudiés étaient: bouchons d'oreilles E-A-R Classic, bouchons d'oreilles double Combat Arms, bouchons d'oreilles ETY·Plugs (ajustement universelle), oreillères Peltor H10A et oreillères Peltor PowerCom Plus. Les oreillères ont aussi été étudiées en combinaison avec les bouchons d'oreilles E-A-R Classic et avec des lunettes anti-projectiles. **Résultats:** La combinaison des bouchons d'oreilles et des oreillères a fourni le plus haut niveau de protection, suivi des bouchons d'oreilles de niveau indépendant, des oreillères et des bouchons d'oreilles de niveau dépendant. Les lunettes anti-projectiles ont diminué l'efficacité des oreillères. **Discussion:** Les résultats de l'étude nous démontrent le niveau de protection de chaque protecteur auditif, mais le meilleur choix dépendra du milieu opérationnel. La combinaison des bouchons d'oreilles de niveau indépendant et des oreillères est la plus efficace, toutefois, cette combinaison n'est pas optimale lorsqu'un certain niveau de communication est requis. Les bouchons d'oreilles devraient être portés lorsque les oreillères nuisent à la vue de l'arme ou lorsqu'elles deviennent incompatibles avec d'autres équipements comme un casque ou des lunettes. Une étude future pourrait inclure différents types de casques d'écoute avec microphone et différentes combinaisons de protecteurs auditifs.

Mots clés: bruit, écoute, personnel militaire, perte auditive liée au bruit, protecteur auditif

INTRODUCTION

Hearing loss in the Canadian Armed Forces (CAF) is a problem that has not lessened over the years. The cost of claims for hearing loss borne by Veterans Affairs Canada is currently more than $180 million annually, including the cost of disability awards, services, and assistive listening devices.[1] CAF members who operate firearms are particu-

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larly at risk for hearing loss because of the high-intensity, short-duration noise exposures, called *impulse noise.* Although it is obvious that hearing protection devices (HPDs) should be worn during weapons firing, two commonly asked questions are (1) what type of HPD should be worn and (2) how many rounds can be fired without risk of hearing loss? The recently updated Military Standard (MIL-STD) 1474E describes two metrics for predicting hearing damage from impulse noise: the Auditory Hazard Assessment Algorithm for Humans (AHAAH) and the equal energy equivalent (of the impulse) averaged over 100 milliseconds (LIAeq100ms).[2] Although a discussion of these metrics is outside the scope of this article, note that the calculations can include the hearing protection provided by different types of HPDs.

Commercially available HPDs can be divided into different categories.[3] Conventional earplugs, such as the E-A-R Classic (3M, St. Paul, MN), and earmuffs, such as the Peltor H10A (3M, St. Paul, MN), are called *passive devices* because they attenuate noise by providing a physical barrier to the sound. Passive devices are generally level independent, meaning they provide the same amount of noise attenuation regardless of the level of noise. Level-dependent devices provide less attenuation for low levels of sound (such as speech) and greater attenuation for higher levels of sound. Passive level-dependent earplugs contain an orifice that acts as a resistive element to acoustic pressure. At low levels, sound passes through the orifice with no resistance. High-level impulses, however, create turbulent airflow in the orifice that increases the resistance, resulting in lower pressure levels in the ear. This effect is typically seen at impulse levels of 110 to 115 decibels of sound pressure level (SPL) and higher.[4] One example of a passive level-dependent device is the Combat Arms earplug (3M, St. Paul, MN), which was designed for protection from impulse noise.

Active HPDs (which can also be level dependent) have electronics that allow features such as active noise reduction (ANR) and enhanced ambient listening. ANR can be effective at reducing low-frequency noise by cancelling noise signals lower than around 1000 hertz (Hz).[5] However, ANR has been shown to be not effective for impulse levels higher than 150 decibels (dB).[6] Devices with enhanced ambient listening allow the user to adjust the volume of ambient sounds, which is intended to allow for greater situational awareness. The Peltor PowerCom Plus communications headset (3M, St. Paul, MN) is an active level-dependent device with a function for enhanced ambient listening. Active HPDs that are specifically for military radio communication are sometimes called *tactical communication and hearing protection systems* (TCAPS).

It is easier to attenuate higher than lower frequencies of sound because of their shorter wavelengths; therefore, conventional HPDs provide greater insertion loss (IL) at higher frequencies. However, for users who have a critical need to discriminate among certain sounds such as speech, music, or other communications, it is beneficial to use a device that provides uniform attenuation of frequencies.[7] Specialty devices such as ETY·Plugs (Etymotic Research Inc., Elk Grove, IL) use a tuned resonator and acoustic resistor that allow for equal reduction of sound frequencies. This type of device is potentially useful for personnel who are not shooting but are working in the vicinity of the noise.

The Canadian Standards Associated rates HPDs as Class A, B, or C depending on the attenuation provided at different frequencies.[7] Other rating systems include the noise reduction rating (NRR)[8] and the single number rating (SNR),[9] in decibels, which serve the purpose of providing a single value to describe the effectiveness of an HPD. None of these rating systems are valid for impulse noise. The performance of HPDs with impulse noise must be measured according to American National Standard Institute and Acoustical Society of America (ANSI/ASA) S12.42[10] using an acoustic test fixture (ATF). The metric is called the *impulse peak insertion loss* (IPIL). This article describes IPIL measurements for several categories of HPDs following the procedures described in ANSI/ASA S12.42. The purpose of this work was not to characterize the performance of a particular device but rather to compare the IPIL of different categories of devices.

METHODS

Equipment

The measurements were performed using a 45CB ATF and a 67SB blast probe microphone (G.R.A.S. Sound & Vibration, Holte, Denmark). The ear canals of the ATF were heated to 37°C before the measurements. Data were acquired with a four-channel Soundbook MK2 system running Samurai software (SINUS Messtechnik GmbH, Leipzig, Germany) at a sampling rate of 204.8 kilohertz (kHz). A WeatherHawk Signature series model 916 weather station (WeatherHawk, Logan, UT) was used to log temperature, humidity, and wind speed.

Set-Up

The measurements were performed at Canadian Forces Base Meaford in June 2014 on a clear, sunny day with an average temperature of 22.2°C (range 20.6°C–25.1°C) and average humidity of 39%. The average wind speed was 2.0 metres/second (maximum 4.7 m/s). The shooting range was a grass-covered open field.

The sensor positions are shown in Figure 1. The ATF was placed on the ground, 10 meters directly in front of the noise source (a shooter standing with a CAF rifle). The blast probe was placed 2 meters to the side of the ATF, angled to point toward the noise source to measure the reference signal. The setup was chosen to meet the requirements of ANSI/ASA S12.42 for measurement configuration and noise source level and was not intended to measure the noise level for hearing protection at the shooter's ears.

Hearing protection devices

The following commercial HPDs were tested: E-A-R Classic earplugs, Combat Arms double-end earplugs, ETY·Plugs earplugs (standard fit), Peltor H10A earmuffs, and Peltor PowerCom Plus earmuffs. The E-A-R Classic, Peltor H10A, and Combat Arms (green end) are passive and level independent. The Peltor PowerCom Plus was measured in the passive mode (powered off), so it was also considered to be a passive level-independent device. The Combat Arms plug (yellow end) is a passive level-dependent device, and the ETY·Plugs are a specialty device. The E-A-R Classic plugs were also measured in combination with the Peltor H10A earmuffs. All of the earplugs were new. The earmuffs had previously been used in the laboratory by research participants and were in slightly used but good condition.

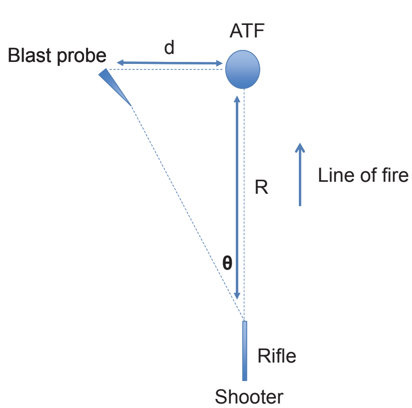

Figure 1. Measurement setup with the ATF placed at a distance R = 10 m from the firing point and the blast probe at d = 2 m from the acoustic text fixture (ATF).

When safety glasses are worn with earmuffs, they create a gap between the ear cup and the head, which creates leakage of sound into the ear cup, reducing the effectiveness of the muffs.[11] A pair of standard-issue ballistic glasses was placed on the ATF, and measurements were taken with the Peltor H10A and Peltor PowerCom Plus muffs, alone and in combination with the E-A-R Classic plugs.

Test procedure

The microphone signals from the ATF left and right ears and the blast probe were synchronized and recorded simultaneously. All microphones were calibrated to 114 dB at 250 Hz using a 42AP pistonphone (G.R.A.S. Sound & Vibration, Holte, Denmark). Open-ear measurements (no HPD in place) were recorded for three shots. For each HPD, five shots were fired to obtain five measurements of IL. Between each shot, the HPD was removed and re-fit by the same person (the author) for consistency. At the end of the HPD testing, open-ear measurements were again recorded for three shots.

Data analysis

The IL of an HPD is the difference between the open-ear (no HPD) and closed-ear (with HPD) SPLs, measured inside the ear. Ideally, one could measure the open-ear response, place the HPD on the ATF and measure the closed-ear response, then subtract the second measurement from the first to obtain the IL. However, this approach assumes that the source signal was identical for both measurements. With impulsive noise sources, there are likely to be small variations in the signal between trials, particularly in an outdoor environment. For this reason, the free-field, or reference, signal is measured with the blast probe. The difference between the free-field and the open-ear signal is called the *transfer function of the open ear* (TFOE). The TFOE is a characteristic of the ATF that does not change between measurements. For a given source and measurement configuration, the TFOE, or HFF, is a function of frequency, f, defined as

$$H_{FF}(f) = \frac{F(P_{open})}{F(P_{FF})}, \quad (1)$$

where F is the Fourier transform and Popen and PFF are the pressure-time signals measured at the open-ear and free-field microphones, respectively. The transfer function HFF can be averaged over the number of repetitions, in this case six (three open-ear measurements before and after testing). The average HFF for each ear

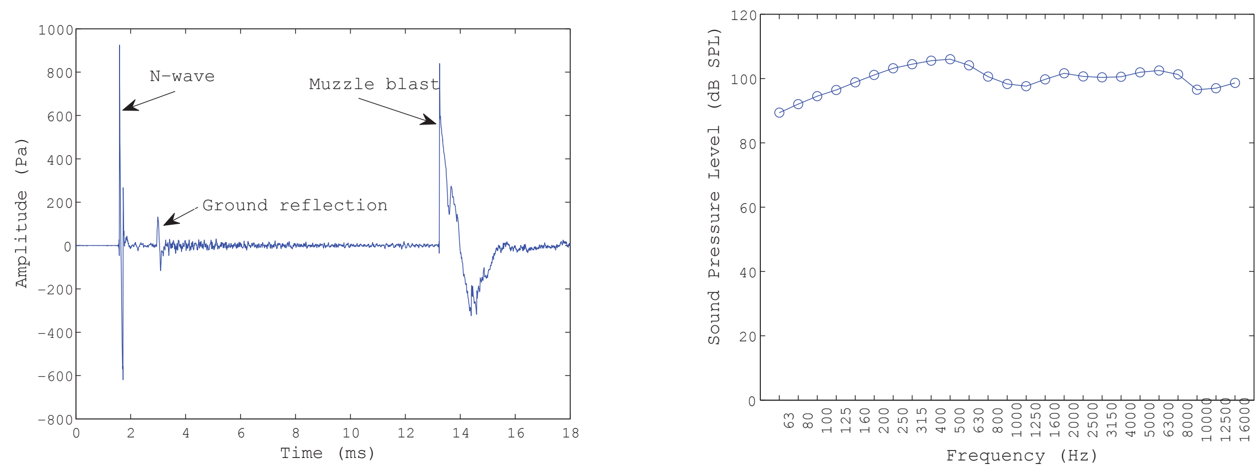

Figure 2. Sample pressure-time signal (left) and spectrum (right) of the rifle noise source at a distance of 10 m, measured at the blast probe on the ground. The peak amplitude of the N-wave is 937 Pa or 153.4 dB.

can then be used to estimate the open-ear signal as a function of time, *t,* as

$$P_{Est-Open}(t) = F^{-1}\left[H_{FF}(f) \times F\left(P_{FF}(f)\right)\right]. \quad (2)$$

The pressure-time signal recorded inside the ear with the HPD in place is called the closed-ear signal, *P*closed. The IPIL can be calculated using the difference of the peak pressure values of *P*Est–Open and *P*closed,

$$\max\left|P_{Est-Open}\right| - \max\left|P_{closed}\right|. \quad (3)$$

Converting to decibels, the IPIL is

$$IPIL = 10\log_{10}\left(\frac{\max\left|P_{Est-Open}(t)\right|^2}{\max\left|P_{closed}(t)\right|^2}\right), \quad (4)$$

which is calculated for each ear, HPD sample, and trial.[10] The IPIL is calculated using the time signal and therefore represents the combined energy reduction at all frequencies. However, calculating the IL in the frequency domain, in 1/3 octave bands, is also of interest. Taking into account the TFOE, the IL as a function of frequency, *IL,* can be calculated as

$$IL(f) = L_{FF}(f) - L_p(f) + H_{FF}(f), \quad (5)$$

where *L*FF and *L*p are the 1/3 octave band SPLs in the free field and at the eardrum of the protected ear, respectively. The IL results in 1/3 octave bands have been reported by other authors;[4,6] however, this calculation is not described in ANSI/ASA S12.42.

RESULTS

Free-field source signal

A sample of the free-field source signal is shown in Figure 2. The signal was measured 10 m in front of the muzzle, with the blast probe on the ground. For rounds of supersonic speed, there is an N-shaped boom signal at measurement positions in front of the muzzle, called the *N-wave.*[12] The N-wave and muzzle blast are easily distinguishable, occurring about 11 milliseconds apart. The ground reflection is seen about 2 milliseconds after the N-wave. For this measurement configuration, the N-wave peak was higher than the muzzle blast at 937 pascals (Pa), or 153.4 dB. The 1/3 octave band spectrum on the right side of Figure 2 shows a broadband signal with an even distribution over most of the range of human hearing.

Transfer function of the open ear

The TFOE of both ATF ears are shown in Figure 3. Within the six measurements, the range of energy values was generally within 3dB at 1/3 octave band frequencies between 63 Hz and 16 kHz. The exception was at 4 kHz, where the ranges of energy values were 5.3 and 4.2 dB for the left and right ears, respectively. The TFOE for both ears shows the expected response of the human auditory system, with the highest sensitivity between 2 and 4 kHz.

Impulse peak insertion loss

The IPIL of each HPD was calculated using the free-field source signal, the TFOE, and closed-ear measurements. Figure 2 shows that the amplitude of the N-wave

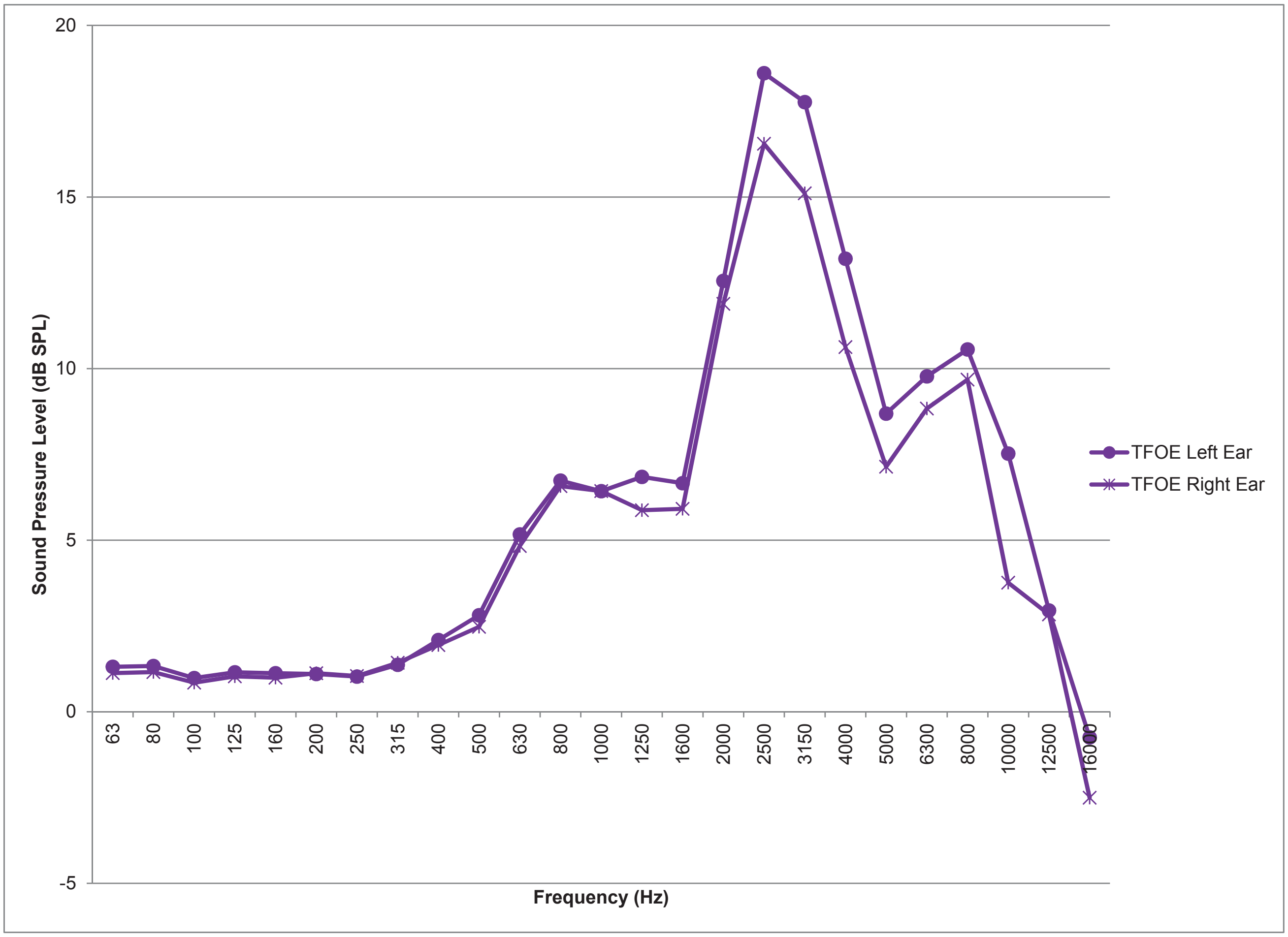

Figure 3. Transfer function of the open ear (TFOE) for the GRAS Acoustic Test Fixture.

was higher than that of the muzzle blast. Because the IPIL calculation uses only the highest instantaneous peak value (Equation 3), the IPIL values reported here apply to the N-wave. Calculation of the IL in 1/3 octave bands using an instantaneous peak is not possible; the duration of the signal must be long enough to obtain sufficient resolution at the low-frequency end of the spectrum. Therefore, a longer time window that included both the N-wave and the muzzle blast was used to calculate the IL in 1/3 octave bands.

The average IPIL values are shown in Table 1 for each HPD configuration. Ranges are shown rather than standard deviations because of the small number of trials (five each). The highest IPIL values (49.5 dB and 48.7 dB for the left and right ears, respectively) were achieved by double protection (E-A-R Classic plugs and Peltor H10A muffs), and the lowest values (15.6 and 8.7 dB for the left and right ears) were obtained when ballistic glasses were worn with an earmuff (Peltor PowerCom Plus).

The IL in 1/3 octave bands was averaged across trials for each HPD. When the IL is presented as a function of frequency, the bone conduction limits can be observed. Because sound is transmitted both through the bony structures in the head and by air conduction through the ear canal, there is an upper limit to the protection that can be provided by blocking the ear canal. These bone conduction limits have been quantified in octave bands experimentally[13] and have been plotted with the IL results for reference. The earplug results shown in Figure 4 are the average for the left and right ears. The IL of the E-A-R Classic at 1 and 2 kHz and the Combat Arms, green end, and ETY·Plugs at 2 kHz exceeded bone conduction limits. The E-A-R Classic plugs provided the highest broadband IL of the earplugs. The earmuff results are shown in Figure 5. Bone conduction limits were exceeded at 1, 2, 4, and 8 kHz for the double protection case (Peltor H10A and E-A-R Classic) and at 2 Hz for both muffs alone. The wearing of ballistic glasses generally reduced the IL between 250 Hz and

16 kHz by about 5–15 dB for the Peltor H10A and by 5–30 dB for the Peltor PowerCom Plus.

DISCUSSION

ANSI/ASA S12.42 requirements not met

Several requirements in ANSI/ASA S12.42 were not achieved during these measurements:

1. Band force of the earmuffs was not measured;
2. One sample of each HPD type was measured instead of the required five;
3. Low (130–134 dB) and high (166–170 dB) impulse ranges were not used;
4. The noise source exceeded the middle testing range (148–152 dB) by 2 dB; and
5. The impulse duration was shorter than required (< 0.5 ms).

The earmuff band force is an indicator of the tightness of seal that the device provides over the ears when properly fitted. The instrumentation required to measure the band force of the earmuffs was not available; this should be corrected for future measurements. Five samples were not available for all of the devices. Because the main objective was to compare the results for different types of passive HPDs rather than to characterize the IL of a particular device, it was decided that five measurements of one sample of each device would provide sufficient data.

Noise source signals that meet ANSI/ASA S12.42 requirements include explosives[4,6] and acoustic shock tubes.[14] In the current study, a rifle was used as the noise source. The measurement configuration (Figure 1) seems counterintuitive if one is considering hearing protection for the shooter. It is emphasized that the measurement set-up was used to achieve the requirements for the noise source signal in terms of the time signal (i.e., no significant reflections within 5 ms) and level. This is different from the signal that is experienced at the shooter's ears, but the results can be applied generally to exposures in the 150-dB peak range. Although the intended noise source was the muzzle blast, the blast probe was positioned such that the N-wave was of higher amplitude than the muzzle blast. The N-wave is not ideal for IPIL measurements because of its very short duration (on the order of microseconds rather than milliseconds). It is possible to avoid the N-wave in the measurements by placing the ATF and blast probe 90° to the muzzle; this configuration should be considered for future measurements. Another option is to use a weapon that has a subsonic muzzle speed as the noise source.

Insertion loss results

The E-A-R Classic plug provided the largest IPIL of all the devices tested in isolation (average of 37.8 dB and 40.6 dB for the left and right ears, respectively), followed closely by the ETY·Plugs (35.1 dB and 39.0 dB, respectively). This result was unexpected. The ETY·Plugs have an SNR rating of 18 decibels, compared with the E-A-R Classic SNR rating of 28 dB, indicating that the E-A-R Classic provides better protection in continuous noise. The results suggest that this specialty device has the potential to allow both undistorted ambient listening and effective protection from impulse noise. Previous measurements of the ETY·Plugs showed average IPIL of about 15, 19, and 28 dB using source signals in the

Table 1. Average IPIL and ranges for each HPD and HPD combination for the left and right ears

HPD	Left		Right	
	IPIL, dB	Range, dB	IPIL, dB	Range, dB
E-A-R Classic	37.8	33.7–42.1	40.6	38.7–42.0
Combat Arms Green	28.8	21.2–33.3	27.6	21.5–38
Combat Arms Yellow	21.7	20.2–24.2	19.5	18.0–21.4
ETY·Plugs	35.1*	32.6–39.8*	39.0*	38.0–40.1*
Peltor H10A	19.2	15.1–21.6	17.1	12.8–25.6
Peltor H10A and EAR Classic	49.5	46.1–54.3	48.7	45.7–51.2
Peltor PowerCom Plus	31.6	30.3–34.6	34.1	31.5–37.8
Peltor H10A and glasses	16.4	14.9–18.6	12.9	10.9–15.6
Peltor H10A, E-A-R Classic, and glasses	47.3	46.3–48.5	44.1	40.5–47.6
Peltor PowerCom Plus and glasses	15.6	14.3–16.3	8.7	5.2–10.8

* Data from four trials. One trial was omitted because of an anomalous result.
IPIL = impulse peak insertion loss; HPD = hearing protection device.

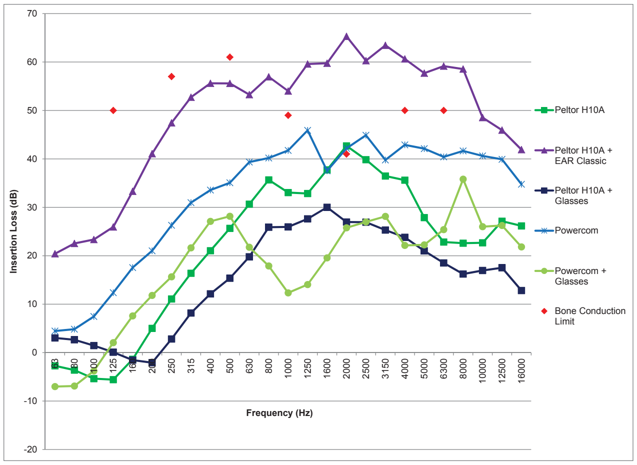

Figure 4. Insertion loss of the earplugs. Note that bone conduction limits were exceeded by the E-A-R Classic earplugs at 1, 2, and 8 kHz and by the Combat Arms, green end, and ETY·Plugs at 2 kHz.

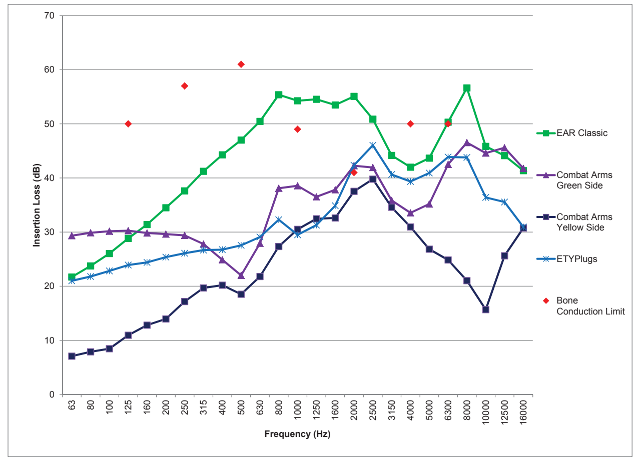

Figure 5. Insertion loss of the earmuffs. Note that bone conduction limits were exceeded at 2 kHz for both types of muff alone and 1, 2, 4, and 8 kHz for the double protection case (Peltor H10A and E-A-R Classic).

ranges of 132, 150, and 168 dB, respectively.[14] This indicated level dependence, but with values much lower than the current data. Subsequent measurements using the ETY·Plugs should include different source levels to further investigate the level dependence.

It was expected that there would be differences in IL between the two ends of the Combat Arms plugs. The green (level-independent) end provided IPIL values of 28.8 and 27.6 dB for the left and right ears, respectively, and the yellow (level-dependent) end provided values of 21.7 and 19.5 dB, respectively. The latter results are in agreement with previous results for the single-ended (level-dependent) Combat Arms plugs.[14]

The IPIL results for the Peltor H10A earmuffs were 19.1 and 17.2 dB for the left and right ears, respectively, and those for the Peltor PowerCom Plus were 31.6 and 34.1 dB, respectively. When the muffs were worn with E-A-R Classic plugs, the IPIL results were similar, indicating that the plugs provided most of the protection. When the muffs were worn in combination with the ballistic glasses, the IPIL was reduced by about 5 dB for the Peltor H10A muffs and by 15–25 dB for the Peltor PowerCom Plus. Given the differences in these results, it could be difficult to apply a general rule for reduction of IL to earmuffs when glasses are worn. Previous work has shown a reduction in earmuff attenuation when safety glasses are worn;[11] however, data using human subjects in continuous noise cannot be directly compared with the current results. In addition, repeated measurements using one ATF do not generate data for a range of human shapes and sizes, which has an effect on earmuff fit.

Overall, the greatest IL was provided by the combination of earplug and earmuff, followed by the level-independent earplugs, earmuffs, and level-dependent earplugs. The specialty device, surprisingly, provided as much protection as the level-independent plugs. The current results can be used with the MIL-STD 1474E metrics. The AHAAH can include hearing protection and includes several default settings corresponding to level-dependent and level-independent earplugs and earmuffs, both passive and active. It also includes settings for double protection. The LIAeq100ms can include hearing protection by using the IPIL. Planned future work includes using the IPIL results from the current study with the LIAeq100ms metric and comparing the results with the AHAAH output using the corresponding default HPD.

The choice of hearing protector is not simply a matter of choosing the one with the highest IL. The balance between required protection and overprotection is difficult; if the HPD provides a high level of protection from impulse noise but does not allow the wearer to hear commands, it poses a safety hazard. The use of double protection is only practical during weapons firing if communications are fed directly to the ear. This could be achieved using earplugs with integrated communication or using a muff-style communications headset over level-dependent earplugs. If wearing earmuffs is not possible because they interfere with sighting the weapon, earplugs should be worn. In addition, it has been shown that when the negative component of the pressure wave exceeds the force of the headband, the ear cups are lifted from the head.[6] It has been suggested that earmuffs should not be used for peak pressure levels greater than 170 dB.[15] In summary, the choice of an HPD for use in impulse noise requires knowledge of the noise exposure, the performance of the HPD specifically in impulse noise (not the NRR or SNR), and the communication requirements of the operational environment. Future work should include measurements of active HPDs and TCAPS and assessment of the current and future measurements using current impulse noise metrics.[2,16]

CONCLUSIONS

Measurements of the IL of several types of HPDs were performed in the interest of hearing conservation during weapons firing. Although the measurements did not meet all of the criteria required by ANSI/ASA S12.42, the results provide a comparison of different types of HPDs for an operationally relevant noise source. The IPIL results can be used with the updated MIL-STD 1474E impulse noise metrics. Future measurements should include different types of HPDs, including TCAPS, and different types of noise sources and measurement configurations.

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