Military Operators (MOs) are exposed to a broad range of impulse noise that can vary greatly in terms of level, temporal and spectral characteristics. The accurate characterization of the performance of hearing protectors is required, to mitigate the hearing damage risk for the MOs working under such conditions. Presently, the accepted method to characterize Hearing Protection Devices (HPDs) performance is based on the measurement of the Impulse Peak Insertion Loss (IPIL); however, this measurement doesn't provide the peak Insertion Loss (IL) per Octave Band (OB). A method for measuring the peak IL per OB for HPDs was developed and is presented in this paper. The concept of an Octave Band Impulse Peak Insertion Loss (OBIPIL) is introduced to account for the HPD peak attenuation at each OB. Using a modified version of the ANSI/ASA S12.42-2010 test setup, the impulse noise signals for a 5.56 mm caliber weapon were recorded. The IPIL and the OBIPIL values of the tested HPDs were computed and are presented for comparison. Moreover, an OBIPIL comparison versus the Bone Conduction (BC) attenuation limits is provided to gauge the attenuation capabilities of each HPD at each OB. A performance behavior for each HPD is presented in the time domain and per OB. Finally, remarks, conclusions, pros and cons of the proposed methodology as well as future work are discussed.

Keywords: Impulse noise, Hearing protection, Insertion loss, Bone conduction
1. Introduction

The Canadian Standards Association (CSA) rates HPDs as Class A, B, or C; this method defines the minimum attenuation at different OBs [1]. Other rating systems include the Noise Reduction Rating [2] and the Single Number Rating [3], 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 under impulse noise is measured according to ANSI/ASA S12.42 [4] using an Acoustic Test Fixture (ATF); this metric is called the impulse peak insertion loss (IPIL) and accounts for HPD peak attenuation for a time domain signal.

This article introduces the concept of OBIPIL with the purpose of accounting for HPD peak attenuation at each OB; hence comparing the peak attenuation with the BC attenuation at each OB becomes possible.

This article:
- Describes OBIPIL measurements for some selected HPDs using a modified test procedure from ANSI/ASA S12.42;
- Presents the IPIL and the OBIPIL measurement results for different HPD types;
- Analyses the IPIL and the OBIPIL results by taking into account the sensitivity of the human hearing system at 2 kHz, and the BC attenuation limits [4], [8] and [9].

2. Methods

Set-Up: The measurements were performed at Canadian Forces Base Connaught in October 2017, on a clear, sunny day with an average temperature of 10.3 °C (range 8.9 °C to 11.7 °C) and average humidity of 63%. The average wind speed was 4.5 m/s (maximum 7 m/s). The shooting range was a grass-covered open field [10].

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 sixteen-channel Siemens LMS system running PLM Software at a sampling rate of 204.8 kHz.

To generate the impulse noise, a Military Operator (MO) was integrated into the ANSI/ASA S12.42 test scenario, as described by Fig. 1.

![Impulse Noise Test setup](image)

Figure 1: Impulse Noise Test setup, using a modified version of the ANSI/ASA S12.42 testing procedure.
The sensors placement respected the following geometry:
- The ATF was positioned at a height of 1.7 meters;
- The distance between the firing weapon and the ATF was 1 meter;
- The relative angle between the sagittal plane of the ATF and the pressure probe was equal to 30 degrees;
- The distance between the pressure probe and the ATF was equal to 0.52 m.
- The ATF was oriented directly facing the impulse noise source within ± 3 degrees;
- The impulse noise source was a 5.56 mm caliber small arm, producing an average peak level of 157 dB at the arm stock.

**Hearing protection devices:** HPDs manufactured by 3M were used for the experiment; the list below shows the utilized HPD systems by product name and (configuration):
- Combat Arms Earplugs Gen IV (Closed vents);
- Combat Arms Earplugs Gen IV (Open vents);
- Peltor X5A Earmuff;
- Peltor X5A Earmuff & Combat Arms Earplugs Gen IV (Closed vents);
- Peltor X5A Earmuff & Combat Arms Earplugs Gen IV (Open vents).

**Test procedure [4]:** 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).

The source signal was not identical for all measurements. It is expected to observe small variations in the signal between trials when using a firearm as the impulse noise source. Therefore, a repetitive measurement approach is needed to confirm the accuracy of the measurements, where the average and standard deviation of the measurements are computed.

Open-ear measurements (no HPD in place) were recorded for five shots, followed by five shots for each HPD system, to obtain five measurements of IL. To assess the HPD system with a fitting change, the HPD system was removed and re-fitted between the firing sequences, by the same person (the first author) for consistency. The measurement sequence is described in Table 1.

<table>
<thead>
<tr>
<th>Table 1: Measurement sequence for each test scenario</th>
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<tbody>
<tr>
<td>a</td>
</tr>
<tr>
<td>b</td>
</tr>
<tr>
<td>c</td>
</tr>
<tr>
<td>d</td>
</tr>
<tr>
<td>e</td>
</tr>
<tr>
<td>f</td>
</tr>
</tbody>
</table>

**Data analysis:** When using the ATF to measure IL, the sound conduction is assumed to travel only via the ATF ear canal pathway, and the measured acoustic parameters during the experiment are defined as follows:
- Free field sound source: $P_{ff}(t)$;
- Sound at the level of the cochlea when the ATF is unoccluded: $P_{ATF\, unoccluded}(t)$;
- Sound at the level of the cochlea when the ATF is occluded: $P_{ATF\, occluded}(t)$.

The IL of an HPD is the difference between the open-ear (no HPD) and closed-ear (with HPD) Sound Pressure Levels (SPLs) measured inside the ear. However, when dealing with impulse
noise, the IPIL must be measured instead. The IPIL is the measurement of the pressure peak attenuation in the time domain raw data and is calculated by using the difference of the pressure peak pressure values of $P_{\text{ATF}_{\text{Unoccluded}}}(t)$ and $P_{\text{ATF}_{\text{Occluded}}}(t)$[4], [5].

When expressed in time domain, the IPIL equation is formulated as follows:

\[
\text{IPIL}(Pa) = P_{k-\text{ATF}_{\text{Unoccluded}}} - P_{k-\text{ATF}_{\text{Occluded}}}
\] (1)

When expressed in decibels, the IPIL is as follows:

\[
\text{IPIL} (dB) = 20 \times \log_{10}(P_{k-\text{ATF}_{\text{Unoccluded}}}) - 20 \times \log_{10}(P_{k-\text{ATF}_{\text{Occluded}}})
\] (2)

Where, $P_{k-\text{ATF}_{\text{Unoccluded}}}$ is the peak pressure measurement when the ATF is unoccluded, and $P_{k-\text{ATF}_{\text{Occluded}}}$ is the peak pressure measurement when the ATF is occluded.

The IPIL measurement in the time domain, does not provide any information about the attenuation capabilities at each OB of the HPD system used to attenuate the acoustic impulse [6], nor does it provide enough information to compare the HPD attenuation capabilities against the BC attenuation, over the OB spectrum. Hence, decomposing the raw time domain signal into time domain signals for each octave subband is the key idea to measure the peak pressure at each octave subband, when the ATF ears are occluded and unoccluded. As a result, the calculation of the attenuation per OB is possible.

When expressed in the time-frequency domain, the peak pressure variation at a specific subband is represented by $OBIPIL_{\text{Subband}}$ and is formulated as follows:

\[
OBIPIL_{\text{Subband}}(Pa) = (P_{k-\text{ATF}_{\text{Unoccluded}}})_{\text{Subband}} - (P_{k-\text{ATF}_{\text{Occluded}}})_{\text{Subband}}
\] (3)

When expressed in decibels, the $OBIPIL_{\text{Subband}}$ calculation is as follows:

\[
OBIPIL_{\text{Subband}} (dB) = 20 \times \log_{10}\left((P_{k-\text{ATF}_{\text{Unoccluded}}})_{\text{Subband}}\right) - 20 \times \log_{10}\left((P_{k-\text{ATF}_{\text{Occluded}}})_{\text{Subband}}\right)
\] (4)

Where, $(P_{k-\text{ATF}_{\text{Unoccluded}}})_{\text{Subband}}$ and $(P_{k-\text{ATF}_{\text{Occluded}}})_{\text{Subband}}$, represent the peak pressure measurement at a subband level, when the ATF is unoccluded and occluded.

Therefore:

\[
OBIPIL_{\text{Subband}} (dB) = 20 \times \log_{10}\left(\frac{(P_{k-\text{ATF}_{\text{Unoccluded}}})_{\text{Subband}}}{P_{\text{ref}}}\right) - 20 \times \log_{10}\left(\frac{(P_{k-\text{ATF}_{\text{Occluded}}})_{\text{Subband}}}{P_{\text{ref}}}\right)
\] (5)

Where, $P_{\text{ref}}$ is equal to $2 \times 10^{-5} Pa$.

Consequently:

\[
OBIPIL_{\text{Subband}} (dB) = (SPL_{k-\text{ATF}_{\text{Unoccluded}}})_{\text{Subband}} - (SPL_{k-\text{ATF}_{\text{Occluded}}})_{\text{Subband}}
\] (6)
Where \((SPL_{k-ATF_{\text{Unoccluded}}})_{\text{Subband}}\) is the peak Sound Pressure Level (in dB SPL) per subband when the ATF is unoccluded, \((SPL_{k-ATF_{\text{Occluded}}})_{\text{Subband}}\) is the peak per subband (in dB SPL) when the ATF is occluded, and \(OBIPIL_{\text{Subband}}(dB)\) is the level variation at a specific subband.

The time-frequency signal decomposition, in this work, is performed by using a nonuniform, perfect-reconstruction filter bank design based on an FFT (no optimization required) [7], with controllable overlap between subbands, and with linear phase response in each subband (no time dispersion). The sampling frequency used for the measured signal is 204.8 kHz, the FFT length is \(2^{15}\) and a Blackman window is used to reduce ripple in the band pass filter response of each channel. Figure 2, summarizes the calculation steps to obtain the \(OBIPIL_{\text{Subband}}(dB)\).

![Diagram](image)

\[
OBIPIL_{\text{Subband}} (dB) = (SPL_{k-ATF_{\text{Unoccluded}}})_{\text{Subband}} - (SPL_{k-ATF_{\text{Occluded}}})_{\text{Subband}}
\]

**Figure 2: \(OBIPIL_{\text{Subband}}(dB)\) calculation steps**

### 3. Results

*Time domain:* The IPIL of five HPD system configurations was calculated as per [4]. Table 2 provides the average IPIL values and the standard deviation, \(\sigma\), for five shots.

Table 2: Average IPIL (in dB) and standard deviation for each HPD system and at each ATF ear when firing with a 5.56mm caliber small arm.

<table>
<thead>
<tr>
<th>Type</th>
<th>HPD</th>
<th>Left</th>
<th>Right</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>IPIL ((\sigma))</td>
<td>IPIL ((\sigma))</td>
</tr>
<tr>
<td>Ear Plugs</td>
<td>Combat Arms (closed vents)</td>
<td>49 (1.7)</td>
<td>48 (1.0)</td>
</tr>
<tr>
<td></td>
<td>Combat Arms (open vents)</td>
<td>33 (0.7)</td>
<td>34 (1.3)</td>
</tr>
<tr>
<td>Ear Muff</td>
<td>X5A</td>
<td>37 (0.8)</td>
<td>36 (0.6)</td>
</tr>
<tr>
<td>Muff &amp; Plugs</td>
<td>X5A &amp; Combat Arms (closed vents)</td>
<td>53 (2.1)</td>
<td>52 (1.9)</td>
</tr>
<tr>
<td></td>
<td>X5A &amp; Combat Arms (open vents)</td>
<td>44 (1.2)</td>
<td>41 (0.6)</td>
</tr>
</tbody>
</table>

The highest IPIL values were achieved by using double protection with closed vents and the lowest values were obtained with open vent ear plugs.
**Time-Frequency domain:** For each HPD system, the average OBIPIL values and the standard deviation at each OB are shown in Figures 3, 4 and 5. The BC attenuation limits are also provided in Table 3. This comparison is necessary to gauge the protection level at some specific OBs especially between 2 to 4 kHz where the human hearing system is known to be very sensitive.

Table 3: Bone Conduction Attenuation Limits (in dB) as per ANSI/ASA S12.42-2010 [4]

<table>
<thead>
<tr>
<th>Frequency</th>
<th>125 Hz</th>
<th>250 Hz</th>
<th>500 Hz</th>
<th>1000 Hz</th>
<th>2000 Hz</th>
<th>4000 Hz</th>
<th>8000 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head not Covered</td>
<td>50</td>
<td>57</td>
<td>61</td>
<td>49</td>
<td>41</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>

Ear plugs with open vents (Fig. 3.) were designed for optimal performance at 2 kHz; the ear plug is showing an important attenuation capability at 2 kHz. However, attenuation is lower for all the other OBs. These characteristics show that the open vent configuration is suitable to allow communication while still protecting the frequency band around 2 kHz.

Ear plugs with closed vents, are providing an attenuation level almost equal to the BC limits for OBs above 1 kHz. When the OBs are below 1 kHz the ear plug is providing a good attenuation without reaching the BC limits. These characteristics show that the closed vent configuration is suitable to provide attenuation over all the OBs, which is convenient for protection.
The Ear Muff (Fig. 4.) is characterised by providing an important attenuation capability at high frequencies above 1 kHz. Below 1 kHz, the attenuation capability of the muffs is well below the BC limits.

Figure 5 shows the experimental results for double protection. The results clearly show that above 1 kHz the attenuation capability of the HPD system is now exceeding the BC limits. However, below 1 kHz the attenuation behavior seems to maintain only the dominant behavior of the plugs with closed vents (Fig. 3.) or of the muffs (Fig. 4.).

Physiologically, sounds travel to the cochlea by using the bone pathway as soon as the attenuation limits provided by that pathway are exceeded [8], hence the extra attenuation capability above the BC limits does not protect the cochlea. Consequently, the effective level of protection reached by HPD combinations depends on nonlinear factors like BC and on experimental fitting that could be maintained constant under experimental conditions.

4. Discussion

Given the increasing need for evaluating new HPD systems (e.g., vented ear plugs, electronic noise reduction devices) and configurations (e.g., helmet with ear plugs, ear muff with ear plugs) under impulse noise conditions, the OBIPIL method is introduced in this paper. The asymmetry of the shock wave radiated by a small arm and the participation of an MO should not significantly impact the measurement accuracy of the IPIL and the OBIPIL since these values are computed from a differential calculation.

However, in the case of this investigation we had the following limitations:

- Practically, it was difficult to implement the test set-up (Fig. 1), because of the geometric (space) limitations.
- The current study assumes that the BC limits that were established using steady-state noise are applicable to impulse noise.
5. Conclusion

A method based on attenuation in octave bands (OBIPIL) is proposed to assess HPD protection level with impulse noises. In addition, the comparison of the OBIPIL results with the BC limits allows an estimation of the effectiveness of the protection level at each OB. Therefore, it becomes possible to compare the effectiveness of different HPD combinations and to better test and design future systems.

Measurements of the IPIL and the OBIPIL of several types of HPD systems were performed during weapons firing. Although the measurements were performed using a modified version of the ANSI/ASA S12.42 standard, the results did provide a comparison of different types of HPDs in the time-frequency domain for an operationally relevant noise source, i.e. small arms.

While the IPIL captures information from only two peak values, the OBIPIL allows analysis of HPD attenuation over the OB spectrum. As a result, it also allows for potential improvement of modeling of impulse noise impact on hearing.

REFERENCES


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