Overview of Developments in the Description and Assessment of High Intensity Impulse Noise Exposure

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ABSTRACT

The precise description and assessment of high intensity impulse noise can be difficult due to the rapid onset-rates, short durations, very high peak noise levels (and overpressures) and the non-linear acoustic behaviour in the near-field of the source. Furthermore, determining the likely impact on hearing is limited by the current tools available for assessing the actual noise exposure/dose, auditory hazard risk and potential (irreversible) hearing damage. This paper provides insight to the recent developments in the measurement, prediction and assessment of impulsive noise exposure. Guidance is given on the relevant standards and guidelines, the range of measurement and prediction methods, impulse waveform pressure-time characteristics, relevant noise metrics/descriptors, models of impulsive noise exposure and hearing damage mechanisms. Recently developed electroacoustic hearing models are explored, including the Auditory Hazard Assessment Algorithm for Humans (AHAAH) and exposure metrics such as Auditory Risk Units (ARU). Other emerging influences and synergistic effects due to ototoxic substances, human vibration and extended work-shifts are investigated. Real-world examples and the mitigation of high intensity impulse noise are explored along with the need for further research and innovation.

1. INTRODUCTION

Exposure to high intensity impulse noise represents a significant occupational noise hazard, especially in certain industries such as defence, mining, trades and industrial plants. Noise Induced Hearing Loss (NIHL) is one of the most prevalent and serious occupational health conditions and is a consequence of being subjected to long term exposure to high noise levels, and exposure to very high peak noise. Compensation claims paid to employees who suffer from some form of hearing loss is estimated to be well into the hundreds of millions globally, and assessing and understanding the health risks to a workers' health have become a key responsibility for employers.

In relation to the description and assessment of high intensity impulse noise, problematic issues are associated with the accurate measurement and prediction of impulsive noise events due to the very short durations, rapid onset-rates, large amplitudes (high peak noise levels/overpressures) and the non-linear acoustic behaviour close to the source. In addition, the previous tools available for assessing the actual noise exposure, auditory hazard risk and potential hearing loss are limited. For impulse noise, there is a need for determining the number of peak events above a certain threshold that is allowable before the risk of permanent NIHL becomes too high.

Recent developments in the description and assessment of impulsive noise exposure provide improved guidance in the areas of impulse measurement and prediction methods, applicable noise exposure descriptors and criteria, models of hearing damage mechanisms and new methods for determining impulsive noise exposure.

2. RELEVANT STANDARDS AND GUIDELINES

A brief overview is provided of the relevant standards, legislation and guidelines within Australia and internationally. There have been recent developments in the methods of measurement, prediction and assessment of impulsive noise exposure. The primary standards that relate to impulse noise, with a brief summary, include:

- AS/NZS 1269, *Occupational Noise Management* (comprising 5 parts, 0 to 4; latest version: 2005)

AS/NZS 1269.1 (*Part 1: Measurement and assessment of noise immission and exposure*) stipulates the preferred measurement quantities and metrics for occupational exposure of $L_{Aeq,T}$ (or $E_{A,T}$) and L_{peak}. The L_{peak} level is used to determine impulse noise exposure. AS/NZS 1269.3 (*Part 3: Hearing protector program*) Appendix B provides a normative method for selecting a hearing protector for when L_{peak} exceeds $L(crit)_{peak}$: for impulse noise from small-calibre weapons and tools, use Class 5 hearing protection (HP); and for impulse noise from large-calibre weapons and blasting, use double HP with at least Class 3 earplugs and earmuffs of any classification.

- ISO 1999, *Acoustics – Estimation of noise induced hearing loss*

ISO 1999 :2013 specifies a method for calculating the expected noise-induced permanent threshold shift in the hearing threshold levels of adult populations due to various levels and durations of noise exposure. It provides the basis for calculating hearing disability when hearing threshold levels at measured audiometric frequencies exceed a certain value. Estimates of NIHL are based on time-varying exposures to steady-state noise and may not be reliable for impulse noise (sound levels greater than 140 dB); the standard therefore may not provide valid estimates of hearing loss for impulse noise. Note: AS ISO 1999:2003 (based on old ISO 1999 :1990 version, including noise exposure estimation) has been superseded and the new version, ISO 1999:2013, now applies.

- ISO 9612, *Acoustics – Determination of occupational noise exposure – Engineering method*

ISO 9612 :2009 provides an engineering method and equations to calculate time-averaged sound exposure levels. Like ISO 1999, the standard does not adequately address impulse noise, apart from noting highest L_{Cpeak} levels, and the standard is therefore less likely to provide valid estimates of noise exposure for impulse noise.

- AS/NZS 3817, *Acoustics – Methods for the description and physical measurement of single impulses or series of impulses*

AS/NZS 3817 :1998 is a direct text adoption (DTA) of the international ISO 10843 :1997 standard, described below. This standard is likely to be reconfirmed as a DTA of the latest version of ISO 10843; if this is the case then AS/NZS 3817 will be withdrawn and the new standard will be AS ISO 10843.

- ISO 10843, *Acoustics – Methods for the description and physical measurement of single impulses or series of impulses*

ISO 10843 :1997 (with Technical Corrigendum 1 :2009) describes preferred methods for the description and the physical measurement of single impulsive sounds or short series of impulsive sounds and for the presentation of the data. It does not provide methods for interpreting the potential effects of series of impulses of noise on hearing and receiver points. ISO 10843 provides the range of parameters and metrics that define impulse noise characteristics, and methods for measurement of phase-sensitive parameters and time-integrated quantities.

- ISO 13474, *Acoustics – Framework for calculating a distribution of sound exposure levels for impulsive sound events for the purposes of environmental noise assessment*

ISO 13474 :2009 provides an engineering method for calculating a statistical distribution of event sound exposure levels at locations which are some distance from high-energy impulsive sound sources. Hence, it is specifically intended for environmental noise assessment at distance and not for the assessment of the risk of occupational noise exposure. However, the standard does provide guidance on the determination of impulse source characteristics such as the measurement and estimation of sound emission properties of muzzle blast and projectile sound. It generally uses the methods defined in ISO 17201 with some modifications.

- ISO 17201, *Acoustics – Noise from shooting ranges* (comprising 5 parts, 1 to 5)

ISO 17201 provides guidance for calculating the sound propagation of shooting sound from shooting ranges, primarily for environmental noise assessment purposes. The standard applies to firearm calibres of less than 20 mm or explosive charges of less than 50g TNT equivalent. The five parts of the standard include: ISO 17201-1 (*Part 1: Determination of muzzle blast by measurement*), ISO 17201-2 (*Part 2: Estimation of muzzle blast and projectile sound by calculation*), ISO 17201-3 (*Part 3: Guidelines for sound propagation calculations*), ISO 17201-4 (*Part 4: Prediction of projectile sound*), ISO 17201-5 (Part 5: *Noise management*). These parts are described further in section 4 of this paper. A new Part 6 has been proposed for guidance on occupational noise exposure from impulsive shooting or blast noise at close range to the source, and is currently under preparation.

- MIL-STD-1474, *US Military Standard*

The United States' Department of Defence has developed a Design Criteria Standard, MIL-STD-1474 (latest version: MIL-STD-1474E, issued 15th April 2015), for *Impulsive and Continuous Noise of Platforms and Weapons Systems* (*Design Criteria – Noise Limits*). It provides noise criteria for designing defence materiel having noise levels that minimise the risk of permanent noise induced hearing loss. While this standard is not enforceable in Australia, it is a useful guideline for the impact of high intensity impulsive noise, in lieu of a suitable AS. The MIL-STD-1474E (Appendix B – Impulsive Noise) uses two methods to determine the noise risk associated with impulsive noise that exceeds an L_{Cpeak} of 140 dB, including a new exposure metric, the Auditory Risk Unit (ARU). The MIL-STD-1474E recommends noise criteria, based on the ARU metric, to minimise the likelihood of permanent hearing loss; which is described further in section 5 of this paper.

- Other relevant standards and guidelines include: European Union (EU) Directive 2003/10/EC, NORDTEST Method NT ACOU 112 (2002-05), American standard ANSI S3.44, US OSHA standard 1910, US NIOSH Standard (*Criteria for a Recommended Standard – Occupational Noise Exposure*), UK Control of Noise at Work Regulations L108 and the World Health Organization (WHO) *Occupational Noise Exposure Criteria*.

National legislation in Australia (WHS Act 2011, WHS Regulations 2011, WHS Code of Practice) states that employers must ensure employees are not exposed to noise levels within the workplace that exceed the national exposure standard (NES) for noise; i.e. $L_{Aeq,8h}$ of 85 dB(A) or L_{Cpeak} of 140 dB(C).

3. IMPULSE CHARACTERISTICS AND DESCRIPTORS

The sudden onset of a sound is defined as an impulse. High-level, short-duration noise can arbitrarily be categorized as impulse noise, which is the product of explosive devices (e.g. gunfire), or impact noise, which is generated by the forceful meeting of two hard surfaces (e.g. hammering, impact wrenches).

Impulse noise is typically characterized as having the following main properties:

- rapid onset-rates – the onset rate is the slope in dB/second of the straight line approximation between the starting point and end point of the impulse waveform time history (typically greater than 10 dB/s).
- very short durations – the first positive pulse duration can be of the order 1 to 5 ms for weapon firing and a pulse width of up to 10 ms for some sources.
- large amplitudes for high intensity sources, i.e. very high peak noise levels (greater than 130 dB and up to 180-190 dB).
- extreme overpressures for high energy sources (greater than 1 kPa and up to 100 kPa).
- high-energy impulsive sound sources comprise prominent low-frequency components.

The typical descriptive measures of impulse noise are the initial peak level and the duration of the first overpressure. This is the A-duration and is typically less than 1 millisecond (ms) for small-medium calibre firearms (e.g. rifles, machine guns) and several milliseconds for large calibre weapons (e.g. cannons). For impact noise, the two principal descriptors are the highest peak in a series of successive peaks (i.e. reverberations) and the so-called B-duration, the duration from the highest peak level to a point in time when the reverberations have decayed by either 10 or 20 dB. B-durations typically range from 50 to 300+ ms.

The character and prominence of the impulse at an immission or receiver point depends on the character of the emitted sound, the distance and propagation path from the sound source and the background noise.

In the near-field of impulse sources (within about 20m to 30m for large calibre weapons, depending on source) the acoustic field exhibits non-linear behaviour, and presents difficulties for accurately measuring or predicting noise levels in this region. Many studies have found that non-linear effects can occur in high pressure wave propagation, and as a result, application of non-linear mathematical methods (e.g. Hilbert transform, causality indices) are employed to describe high intensity sound waves and are justified by the fact that linear approaches do not provide accurate solutions for high pressure acoustics (Lenchine & Teague, 2008).

The region within which non-linear acoustics applies is above 154 dB (1 kPa) – this is where strongly non-linear waves and shock waves are generated (where dynamic pressure is close to static pressure of 100 kPa or 194 dB), leading to different sound speeds in different parts of the wave and causing additional/non-linear attenuation. Distances should be 2 – 3 times longer than the longest wavelength in order for lowest frequencies to fully develop.

The two primary sound generating sources from firearm/weapon firing are the muzzle blast (sound from explosion inside gun barrel, rapid directional volume expansion of gases and resulting pressure waves) and the projectile sound (non-linear sonic boom of supersonic projectiles plus any turbulence, scattering, reflection).

4. MEASUREMENT AND PREDICTION METHODS OF IMPULSE PROPAGATION

4.1 Measurement Methods

ISO 10843 describes preferred methods for the physical measurement of single impulsive sounds or series of impulsive sounds. It provides the range of parameters and metrics that define impulse noise characteristics, and specifies methods for: 1) measurements of phase-sensitive parameters (such as peak sound pressure level and duration, which characterises the variation of sound pressure with time) and 2) measurements of time-integrated quantities (such as frequency-weighted sound exposure level or sound energy level). However, it does not provide methods for interpreting the potential effects of series of impulses of noise on hearing and receiver points.

ISO 17201 provides guidance for calculating the sound propagation of shooting sound from shooting ranges. The standard applies to firearm calibres of less than 20 mm or explosive charges of less than 50g TNT equivalent, and applies at distances where peak pressures are below 1 kPa (154 dB), outside the non-linear acoustic region. Energy-based levels (L_{AE}, L_{CE}) are used to describe or assess annoyance due to impulse noise (for environmental noise assessment purposes) and maximum or peak levels (e.g. L_{IAmax}) may not be considered valid.

ISO 17201-1 (*Part 1: Determination of muzzle blast by measurement*) provides an engineering method for determining the angular source energy distribution of a firearm muzzle blast from measurements. The source energy, its directivity and spectral structure can be used as input for sound propagation models for environmental noise assessment. The angular source energy distribution levels, $L_q(\alpha_n)$, are estimated on the basis of the sound exposure level measurements, $L_E(r_m,\alpha_n)$, at N discrete angles α_n at the distance r_m (assuming rotational symmetry). Due to ground reflections when measuring above ground, the sound exposure level $L_E(r_m,\alpha_n)$ will also depend on rotational angle β; however, corrections are provided to remove ground reflections. In order to calculate the total source energy and to provide a continuous directivity function, a curve fitting for the angular source energy distribution level is needed, and curve-fitting methods describe the periodic behaviour of the directivity function.

Detailed measurement procedures and sound data requirements are provided in ISO 17201-1. At least five measurements of the sound exposure, $E(\alpha,r_m)$, are required to be made at each microphone position (and angular increment step should not exceed 45°). Simultaneous measurements should be made at all microphone positions; however, measurements may be made sequentially but two microphones should be used with one microphone remaining at the same position. If the peak sound pressure level exceeds 154 dB at any of the microphone positions, the measurement distance shall be increased. The peak sound pressures should preferably be read from the time/pressure signal, where the error due to limited equipment high-frequency response can be corrected.

Aside from detailed sound level meter measurements of impulse noise, one common method used to assess occupational noise exposure is that of personal noise dosimetry sampling. However, there are serious limitations to obtaining accurate and reliable measurements of impulsive noise levels using dosimeters. This is due primarily to the limitations of most standard dosimeters to maximum peak levels of 140 dB (high impulse levels often exceed this measurement range threshold) and the occurrence of extraneous peak events due to accidental or intentional tapping/knocking the dosimeter while being worn.

4.2 Prediction Methods

ISO 17201-2 (*Part 2: Estimation of muzzle blast and projectile sound by calculation*) provides methods for estimating the acoustic source data (i.e. spectral angular source energy distribution) of muzzle blast and explosions and the source data of projectile sound on the basis of non-acoustic data for firearms. This part effectively provides an interpolation method between measurements of muzzle blast. Firearm muzzle blast is highly directive, and both the angular source energy distribution and spectrum vary with angle from the line of fire.

The method is separated in two parts: firstly, the acoustic energy of the shot is estimated; secondly, the directional pattern of the source is applied and the spectrum calculated. The procedure allows the use of very general data or, if available, specific data to provide a more accurate result. Therefore, the procedure allows the use of alternatives such as default values or specific values for certain parameters. The estimate of the muzzle source energy (from estimating chemical energy, energy conversion efficiency, acoustic energy and Weber propellant energy density parameters) is used to determine the acoustical source data, including blast source directivity, spectrum and projectile sound source energy. This allows the sound exposure to be determined at a reception point, depending on the path length from the source position.

ISO 17201-3 (*Part 3: Guidelines for sound propagation calculations*) provides an engineering method for predicting sound exposure levels of shooting sounds for single shots at a certain receiver point, for open field and non-open field situations. This part uses a modification of the ISO 9613-2 method and also provides guidance on how to calculate other acoustic measures from the sound exposure level. Modelling of projectile sound is specified in ISO 17201-2 and ISO 17201-4. ISO 17201-4 (*Part 4: Prediction of projectile sound*) also gives guidelines for the calculation of the propagation of projectile sound (as far as it deviates from the propagation of other sound) such that for the attenuation for projectile noise, A_{excess}, ISO 9613-2 can also be used. The other attenuation parameters such as divergence, air absorption and non-linear attenuation are specified in ISO 17201-4.

In open field situations, especially in front of the firearm when the distance to the trajectory is short, projectile sound can be a relevant source for the sound exposure level of shooting sound. If a shot is fired in a shooting range, projectile sound is in general of minor importance in the estimation of the sound exposure level at a reception point. However, if measures are taken to reduce the sound emission of the muzzle blast, projectile sound can then become a dominant factor.

The propagation calculation may be performed using ray-tracing or more sophisticated models, which take specific weather conditions into account. To calculate a long-term L_{eq}, the results are weighted with respect to the frequency of occurrence of weather conditions pertinent to the time periods of interest. ISO 17201-3 also provides estimate relations for the conversion of sound exposure level to various L_{max} metrics.

5. MODELS OF HEARING DAMAGE AND NOISE EXPOSURE

5.1 Effects of Noise and Hearing Damage

The effects of impulse noise on the auditory system and likely hearing damage mechanisms are briefly described. Impulse noise creates several special hazards to the human auditory system.

First, the high peak levels associated with gunfire (140–190 dB) may damage the cochlea by causing rapid mechanical failure and injury (Humes et al, 2006, Henderson & Hamernik, 1986). A series of rapidly occurring impulses can be partially attenuated by the acoustic reflex, a reflexive contraction of the middle-ear muscles, while isolated impulses reach the cochlea before the activation of the acoustic reflex. Thus, intense explosions may result in large cochlear lesions and significant hearing losses. This damage is termed “acoustic trauma”, and hearing at most frequencies may be affected. Additional symptoms include a sense of fullness in the ears, speech sounding muffled and a ringing in the ears (i.e. tinnitus). Although some recovery of hearing takes place after an acoustic trauma episode, the individual is often left with a severe, permanent hearing loss (Humes et al, 2006).

The relationship between noise-induced hearing loss and the peak amplitude of an impulse or impact noise is complex. Systematic research has shown that at the lower range of exposure to impulse noise (< 140 dB) or impact noise (< 115 dB), the hearing loss is likely to be proportional to the total energy of the exposure (peak level × number of impulses). However, above these peak sound pressure levels, the auditory system is damaged primarily by the large displacements caused by high peak levels. The dividing line between the “energy” and “peak-level” behaviour is referred to as the “critical level”, taken to be 140 dB but is dependent on the impulse waveform.

Humans experiencing blasts at very high sound levels (> 170-180 dB) may suffer damage to the middle ear, including haemorrhage in or perforation of the eardrum and fracture of the malleus. If the eardrum does not rupture during such an intense exposure, the organ of Corti is likely to rupture off the basilar membrane. When a portion of the organ of Corti ruptures, it does not reattach to the basilar membrane and it eventually degenerates. Individuals with mild or moderate permanent NIHL typically have some structural damage in their cochleas. The damage may initially involve scattered loss of sensory cells, primarily outer hair cells, in the organ of Corti. Permanent NIHL may also result in damage to or destruction of other important structures in the cochlea, including fibrocytes in the spiral ligament and limbus and cells of the stria vascularis (Humes et al, 2006).

For high-intensity low frequency sounds, good consistency has been observed in human and animal studies between the frequency content of the exposure stimulus and the location in the cochlea experiencing the greatest damage or injury. For narrow-band stimuli, the maximum cochlear insult is often one-half to one octave higher in frequency than the exposure stimulus. For broad-band noises and impulses, more commonly at military and industrial sites, the damage is greatest in the high-frequency (i.e. basal) portion of the cochlea. Also, the differences in location of the greatest cochlear damage are accurately reflected in the pattern of hearing loss.

Hearing damage mechanisms relating to impulse noise are difficult to establish with certainty and further research is required. There is a well-defined need for better tools and models for simulating and estimating the hearing damage resulting from impulse noise exposure.

5.2 Noise Exposure and Hearing Models

The accurate determination of the likely impact of impulse noise on hearing and the auditory system is limited by the previous tools available for estimating and assessing the actual noise exposure, auditory hazard risk and potential hearing loss. Theoretical and semi-empirical hearing models provide predictive methods for the estimation of hearing damage mechanisms, damage risk criteria (DRC) and resultant noise exposure. In general, for noise exposure, one can add 10logN to the one shot exposure to determine the noise exposure from N shots.

Advanced electroacoustic, biomechanical and dynamic hearing models have been recently developed and tested. One such model is the Auditory Hazard Assessment Algorithm for Humans (AHAAH) mathematical software model (http://www.arl.army.mil/ahaah), which represents an advance in the evaluation of hearing damage risk associated with impulsive noise (Fedele et al, 2013). The AHAAH algorithms apply pressure response dynamics measured for the external, middle, and inner ear, to bio-mechanically model the ear's non-linear physical response to impulsive sound and accurately determine the strain-induced fatigue occurring in the cochlea's organ of Corti. It models the 95th percentile (most susceptible) human ear. It also applies a user-selected direction from which sound is incident on the ear; sound traveling toward the head along the inter-aural axis is a worst-case condition.

The AHAAH Model calculates the auditory hazard of impulsive sounds by dynamically modelling their transmission from the free field, through hearing protection (if used), through the middle ear, into the inner ear, where noise-induced hearing damage typically occurs. The model includes an active auditory reflex, involving middle ear muscle contractions, which can occur in response to the arrival of an intense sound or in anticipation of the arrival of such a sound. The output of the model is given in Auditory Risk Units (ARUs), which are physically related to damage resulting from displacements of the basilar membrane in the inner ear. The AHAAH model was developed based on the mechanical and fluid dynamic properties of the ear, and includes wave motion analysis of the basilar membrane in the cochlea based on the Wentzel–Kramers–Brillouin wave dynamics method.

The US standard MIL-STD-1474E (Appendix B – Impulsive Noise) uses two methods to determine the noise risk associated with impulsive noise that exceeds an L_{Cpeak} of 140 dB. Note that these new methods supersede the previous MIL-STD-1474D method and the Free-field Exception (FFE) and Proportional Dose (PD) methods. The two methods in MIL-STD-1474E employ the following two metrics for assessing noise exposure:

- $L_{IAeq,100ms}$ metric (equal energy model), and
- Auditory Risk Unit (ARU) metric, calculated from the AHAAH model.

A comparison between the two methodologies is presented in Table B-11 of the standard. The MIL-STD-1474E recommends the following noise damage risk criteria (DRC) to minimise the likelihood of permanent hearing loss:

- a total of 500 ARUs is the maximum allowable 'dose' (within a 24 hour period) for *occasional* exposures (e.g. less than once per week on average), noting that doses greater than 500 ARUs are predicted to produce permanent hearing loss; and
- For occupational exposures occurring *more regularly* (i.e. on average, daily or near daily), the limit should be reduced to 200 ARUs (within a 24 hour period) to reduce the likelihood of permanent hearing loss.

This prescription is based on the direct relation between ARUs, temporary changes in hearing sensitivity and the probability of permanent hearing loss. A dose of 500 ARUs is barely safe, a dose of 200 ARUs is more reasonable as an occupational dose limit where daily exposures could occur. The allowable number of rounds (ANOR) of weapon fire is determined based on noise exposure limits of 200 and 500 ARU.

Inputs to the AHAAH model include the high resolution pressure-time history of the impulse waveform, and the model predicts the resultant transfer functions and in-ear displacements. The AHAAH model and MIL-STD-1474E allow the calculation of the attenuation of different default hearing protection configurations (for both "warned" and "unwarned" scenarios). The Hearing Protector Module (HPM) of the AHAAH software models all hearing protectors as passive level independent linear (LIL) devices. The model includes several level dependent non-linear (LDNL) hearing protector devices (HPDs). These LDNL HPDs are modelled linearly, based on Real Ear Attenuation at Threshold (REAT) measurements performed with the HPDs worn in the closed and the open modes.

Other models have been investigated and include: 1) MIL-STD-1474D, 2) NATO Models, 3) LAeq8 Model. The previously used MIL-STD-1474D standard model has shown to be inaccurate for determining impulse noise injury. The other models have their merits but have generally been shown to be deficient in the prediction of impulse noise impacts compared to the AHAAH Model in a recent review (Wightman et al, 2010). The AHAAH Model has been extensively evaluated, peer-reviewed and fully vetted and is the new standard (as is the case with the current MIL-STD-1474E). Even though the AHAAH Model is the best model currently available, it still requires further refinement in the areas of stapes non-linearity, basilar membrane displacements, reflexes and metabolic exhaustion.

Notwithstanding the advances in hearing models for impulse noise, the correlation between model predictions and actual hearing damage can be deficient or inconsistent. There is a need for extensive comparisons with real-world measurements of impulse noise levels (in field and laboratory) and measurements of actual hearing damage extent, which will inform future improvements to noise injury models and hearing protection requirements.

6. OTHER INFLUENCING EFFECTS

Other emerging influences and synergistic effects due to ototoxic substances, human vibration and extended work-shift periods can increase the risk of hearing loss in combination with noise and impulse noise.

Exposure to ototoxic substances and chemicals such as Volatile Organic Compounds (VOCs) can lead to hearing loss. The extent of hearing loss can be exacerbated through combined exposure to both noise and ototoxic agents. There are three major classes of ototoxic substances: solvents, heavy metals and asphyxiates. Activities where these substances may become an issue include painting, construction, fuelling, degreasing, weapons firing and fire-fighting. Ototoxic substances are often present in marine, mining, vehicle and defence industries, specifically fuels and carbon monoxide in engine spaces and maintenance personnel who are exposed to fuels, metals and solvents. Recent review papers provide an overview of ototoxic agents and effects (Mahbub et al, 2016, Teague et al, 2016).

Live weapon firing (large and small-medium calibre) is known to generate ototoxic chemicals, including lead, manganese, arsenic, hydrogen cyanide and carbon monoxide (and toluene compounds), via airborne inhalation and dermal contact (Quemerais, 2013). The airborne concentration and total exposure levels (and the combined effects of different ototoxic agents) will vary depending on a range of factors such as weapon type, propellant charge types, firing scenarios, number/frequency of firing rounds, local weather conditions etc.

The WHS Code of Practice (COP) recommends that monitoring hearing with regular audiometric testing should be conducted where workers are exposed to:

- any of the ototoxic substances (listed in the COP Appendix A) where the airborne exposure (without regard to respiratory protection worn) is greater than 50 per cent of the national exposure standard for the substance, regardless of the noise level; or
- ototoxic substances at any level and noise with $L_{Aeq,8h}$ greater than 80 dB or L_{Cpeak} greater than 135 dB.

The COP also recommends reduced noise criteria of 80 dB (and L_{Cpeak} no greater than 135 dB) in situations where personnel may be exposed to ototoxic substances in addition to noise.

It is also widely recognised throughout industry that there is a link between exposure to hand-arm vibration (HAV) and hearing loss (Pyykko et al, 1987, Pettersson et al, 2012). Note that significant levels of HAV in conjunction with noise may occur with the use of a range of hand tools, pneumatic tools, machinery/vehicles and small to medium calibre automatic firearms. It is suggested that vibration exposure from hand-held tools reduces the blood flow in the cochlea by activating the sympathetic nervous system, leading to increased risk of hearing loss (Pyykko et al, 1987). Longitudinal and case-control studies on subjects who have contracted vibration-related disorders found that subjects with vibration white fingers (VWF) have an increased risk of developing hearing loss. The risk of hearing loss is confounded by several factors such as age, medical, chemical and genetic factors. It is also suggested that whole body vibration (WBV) from operating machinery and vehicles may also increase the risk further.

Work shift durations greater than 8 hours impose a higher health risk to exposed workers. The increased health risk occurs from the additional damaging effect that continued exposure to noise has, once the maximum temporary threshold shift is reached. Risk may be further increased if there is a reduced recovery time between successive working shifts. To compare the effect of noise exposure during a workday other than 8 hours, one needs to normalise this exposure to an equivalent 8 hour exposure $L_{Aeq,8h}$ using equation 9(4) in AS/NZS 1269. In addition, AS/NZS 1269 suggests an additional penalty adjustment to the 8-hour normalised level according to shift length.

A combination of the described effects above can occur in some workplaces which increases the risk of excessive exposure. For example, trades such as aircraft refuellers and vehicle/workshop mechanics can be exposed to high peak levels, extended work-shift noise exposure, ototoxic substances (e.g. fuels, solvents) and HAV, often during the same work-shift. Such situations require careful exposure assessment (including a lower noise exposure standard or additional adjustments) and application of a range of specific control practices.

7. REAL-WORLD EXAMPLES AND MITIGATION

7.1 Examples of Real-world Situations

A subset of real-world examples of the measurement and estimation of noise exposure from a sample of high energy impulse sources is summarised for a range of exposure metrics and criteria.

Noise exposure data was determined for small calibre firearms (SCF, caliber < 10mm) and large calibre weapons (LCW, calibre > 100mm) from high-resolution measurements (sample rate of 200 kHz; time resolution of 0.005 ms; at a range of distances/angles with high-pressure microphones) and calculations conducted in accordance with MIL-STD-1474E (and the AHAAH Model). Exposure calculations were performed for actual near-field operator scenarios (e.g. at or near gun firing position; for cases with and without hearing protection) to determine:

- Calculated in-ear peak pressure level;
- Auditory Risk Unit (ARU) exposure;
- $L_{IAeq,100ms}$ per impulse;
- Calculated $L_{Aeq,8h}$ for a number of impulses;
- Allowable number of rounds (ANOR), based on an ARU of 500 limit;
- Allowable number of rounds (ANOR), based on an ARU of 200 limit.

In terms of hearing protection (see also section 6.2), MIL-STD-1474E and the AHAAH model allow the calculation of the attenuation of different hearing protection device (HPD) configurations (for various scenarios). A range of default HPD options includes earplugs only, ear muffs only and double hearing protection (earplugs plus ear muffs), based on actual Real Ear Attenuation at Threshold (REAT) measurements for a range of available HPDs.

Based on the measured noise levels and the AHAAH model outputs, the ANOR for unprotected exposure and various HPD (at or near gun firing position) is presented in Table 1. An assessment was conducted against the:

1. WHS Legislation with consideration of ototoxic substances ($L_{Aeq,8h}$ NES of 80 dB);
2. WHS Legislation without presence of ototoxic substances ($L_{Aeq,8h}$ NES of 85 dB); and
3. MIL-STD-1474E ANOR using 200 ARU criterion.

Table 1 – Allowable number of rounds for a large-calibre weapon based on different noise criteria

	Allowed Number of Rounds (ANOR), AHAAH Model			
	No HPD	Ear Plugs	Ear Muffs	Plugs & Muffs
		(Default 02)*	(Default 04)*	(Default 06)*
$L_{Aeq,8h}$ WHS adjusted NES, 80 dB	0.1 – 0.2	4 – 6	21	43 – 53
$L_{Aeq,8h}$ WHS standard NES, 85 dB	0.3 – 0.7	13 – 20	70	142 – 178
MIL-STD-1474E Assessment (200 ARU)	0.3 – 0.5	19 – 28	272 – 355	283 – 389

*The Default 02 Ear Plug (within AHAAH model) closely matches the attenuation levels provided by the Class 4 EAR Classic plug, the Default 04 Ear Muff closely matches a Comtec Noise Cancelling Headset, and Default 06 represents double hearing protection.

Table 1 indicates that *unprotected* exposure will result in hearing loss, due to the allowable number of rounds being significantly less than 1. The allowable number of rounds provided is based on an in-ear noise level calculation. When considering all assessment methods, the standard WHS Assessment (using $L_{Aeq,8h}$ criteria) is more conservative than the MIL-STD1474E/AHAAH method and thus allows the least number of rounds per 24 hour period (13 to 20 shots with ear plugs, and 70 shots with ear muffs). When fitting double hearing protection (as is the requirement in the near-field of the LCW), between about 140 and 180 rounds can be fired per 24 hour period.

In the presence of ototoxic substances and with double hearing protection (within 20m to rear and 40m to side of the LCW, using a particular propellant charge), up to approximately 40 rounds can be fired per 24 hour period. If further research shows that no significant ototoxic chemicals are produced from LCW firing, then up to approximately 140 rounds could be fired per 24 hour period. Note that, at the gun operator positions, peak levels of up to 170 dB L_{Cpeak} were measured and $L_{IAeq,100ms}$ levels of up to 140 dB were measured per impulse.

Table 2 provides the current requirements and the recommended updated requirements (for up to 40 rounds in a day) in the near-field of a Large-Calibre Weapon (LCW), noting the high directivity of noise emission.

Table 2 – Current and proposed hearing protection requirements in the near-field of a large-calibre weapon

<table>
<tr><th>Current Requirements</th><th>Proposed Requirements</th></tr>
<tr><td rowspan="2">• Double Hearing Protection (ear plugs + muffs) required within 5 metres of LCW; and
• Single Hearing Protection (ear plugs or muffs) required between 5 and 100 metres of LCW.</td><td>At side of LCW (e.g. 90 or 270 degrees):
• Double Hearing Protection (ear plugs + muffs) required within 40 metres of LCW; and
• Single Hearing Protection (ear plugs or muffs) required between 40 and 200 metres of LCW.</td></tr>
<tr><td>At rear of LCW (e.g. 180 degrees):
• Double Hearing Protection (ear plugs + muffs) required within 20 metres of LCW; and
• Single Hearing Protection (ear plugs or muffs) required between 20 and 100 metres of LCW.</td></tr>
</table>

Note that this assessment is only for LCW firing with a certain propellant charge, and that stricter requirements will probably apply for LCW use with other (larger/noisier) charge types, after confirmation from further noise testing. For small calibre firearms (SCF), it was found that Class 4 ear plugs do not provide satisfactory attenuation for more than 6 rounds in a day, assuming that ototoxic substances are present – hence, a new requirement of at least Class 5 ear muffs (or ideally double HP for up to 200 rounds/day) would be required for SCF.

7.2 Noise Exposure Controls

Where noise exposure controls are required from the measurement data and subsequent exposure risk assessment, the hierarchy of noise control should be applied. Engineering noise control is the preferred method of initial noise reduction, however this is not always practicable. As such, the implementation of mandatory personal protective equipment (PPE) usage and administrative controls are normally applied and used widely within industry.

Administrative control measures recommended and applied throughout industry include job rotation, work scheduling, changing work processes, limiting exposure times for high noise tasks, minimum rest periods, limiting distances from noise hazards, limiting exposure to ototoxic substances and hand-arm vibration, and ensuring equipment is maintained. In particular, for impulse noise from weapon firing, minimum safe distances and the allowable number of rounds (ANOR) should be specified (as described in the last section). For high intensity impulse noise (e.g. from large calibre weapons), double hearing protection is required, i.e. ear plugs and ear muffs. As an example, the combination of a Peltor COMTEC Noise Cancelling Headset (Class 3, 21 SLC_{80}) with either EAR Classic Platinum or HL Bilsom 303L ear plugs (Class 4, 23 SLC_{80}) would meet the primary requirement (selection rule) in AS/NZS 1269.3 (Appendix B) for impulse noise.

Observations made throughout most site surveys showed improper fitting of HPDs. Improper fitting can mean that the HPD will not achieve the attenuation it is designed to provide, and that wearers could be under-attenuating noise levels by up to 10 to 15 dB. Therefore incorrect fitting of HPDs has the potential for workers to be exposed unknowingly to unacceptably high noise levels and subsequent health risks. As such, a recommended action is for training on the use and proper fitting of HPDs for all workers. Personal hearing protectors should be selected and maintained in accordance with WHS Regulation 44, the Code of Practice and AS/NZS 1269.3. Employers should involve workers in the HPD selection process and ensure that workers are comfortable with the HPD of choice.

It is important to note that workers exposed to ototoxic substances may require additional PPE in the form of respiratory protection in addition to suitable hearing protection. This would depend on the number of ototoxic agents exposed to, the exposure levels to specific ototoxic agents (relative to standard exposure criteria for each chemical agent) and the combination with the level of noise exposure.

Noise controls applied within industry for work processes include: buying quiet equipment, acoustic screens in high noise areas (e.g. workshops), silencers and low noise fittings to specific tools, HPDs etc. These solutions have proven effective in reducing occupational noise exposure for high noise areas within Defence (Teague et al, 2014).

WHS legislation requires that workers exposed to high noise levels must have regular audiometric testing. In the area of the measurement of hearing damage, advances in audiometric testing are being made. For example, the measurement of evoked otoacoustic emissions (OAE), such as DP (Distortion Product) and TE (Transient Evoked) testing, could provide a more objective, sensitive and accurate clinical determination of hearing damage (to auditory stimuli in real-time) than standard pure-tone threshold-shift audiometry (Carter, Williams & Seeto, 2015). However, there are limitations in this area given that there are currently no accepted normative values available that can be used in relation to hearing health; and, as such, further research in this area is required.

8. CONCLUSIONS

Recent developments have been made in the description and assessment of impulsive noise exposure. This paper has summarised the relevant standards and guidelines, and has provided an overview of the previous work and applicable methods for impulse measurement and prediction, noise exposure metrics, models of hearing damage mechanisms and approaches to determining the resultant impulsive noise exposure. A discussion on the control of noise exposure highlights the hearing protection and other measures required to mitigate impulse noise.

Recently advanced electroacoustic/biomechanical hearing and noise injury models (such as the AHAAH Model) provide a more robust estimation of likely hearing impact from impulse noise and applicable damage risk criteria. However, there remain limitations to the accuracy and coverage of such models, which require further work including comparisons with real-world measurement data and subsequent verification/validation. Looking forward, in order to minimise severe health risk and injury to workers' hearing from impulse noise, this demonstrates the need to apply a conservative approach and the need for further research and innovation.

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