In-Depth Survey Report

A CASE FOR USING A-WEIGHTED EQUIVALENT ENERGY AS A DAMAGE RISK CRITERION

William J. Murphy, Ph.D. and Chucri A. Kardous

Division of Applied Research and Technology
Engineering and Physical Hazards Branch
EPHB Report No. 350-11a

January 10, 2012

DEPARTMENT OF HEALTH AND HUMAN SERVICES
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

Disclaimer

Mention of any company or product does not constitute endorsement by NIOSH. In addition, citations to websites external to NIOSH do not constitute NIOSH endorsement of the sponsoring organizations or their programs or products. Furthermore, NIOSH is not responsible for the content of these websites. All Web addresses referenced in this document were accessible as of the publication date.

Abstract

Exposure to impulsive noise presents a greater risk of noise induced hearing loss than exposure to an equivalent amount of continuous noise. Noise must be measured, recorded, and analyzed to assess the risk of hearing loss to the persons who are exposed. Traditionally, noise has been analyzed using an equal energy approach where the measured noise exposure is equated to an allowable noise exposure for an eight-hour work day. The National Institute for Occupational Safety and Health (NIOSH), the US Environmental Protection Agency (EPA) and the Department of Labor (DOL) have conducted separate risk analyses that estimate allowable exposure levels for an eight-hour day between 80 and 90 dB sound pressure level time-weighted average. The most recent of these analyses (Prince et al. 1997) established the NIOSH Recommended Exposure Level (REL) of 85 dB. Impulsive noise produced by the collision of objects or the rapid expansion of gases or chemicals presents additional risk for which NIOSH, EPA and DOL suggest that no exposures should occur beyond a critical level of 140 dB SPL. The Department of Defense (DOD) uses the MIL-STD 1474D as its current method to assess impulsive noise exposure (MIL-STD 1474D, 1997). MIL-STD 1474D is based the peak sound pressure level, the B-duration (reverberant decay) of the impulse, and the number of impulses one is exposed to. Other researchers have proposed damage risk criteria focused on different features of the impulsive waveform.

NIOSH has several databases of impulses for gunshots, explosive discharges, manufacturing noises and acoustic shock tube discharges where the free-field impulse and the occluded impulse in an acoustic test fixture were recorded simultaneously. NIOSH has analyzed audiometric databases of impulsive noise exposures for humans and another for chinchilla. These exposure databases were evaluated by estimating the permanent and temporary threshold shifts and comparing the goodness of fit and discrimination for the various damage risk criteria. This report will summarize the background information for the different damage risk criteria. Generally, the impulsive noise reduction performance of a hearing protection device can be described by the reduction of the peak sound pressure level from free-field to occluded ear for the range of exposures 130 to 170 dB. NIOSH evaluated three damage risk criteria (MIL-STD 1474D, A-weighted equivalent 8-hour level L_{Aeq8}, and the Auditory Hazard Assessment Algorithm for Human (AHAAH)) with the Albuquerque Blast Overpressure exposures and the L_{Aeq8} was found to provide the best fit and greatest discrimination for exposures. Similarly, L_{Aeq8} was found to give the best-fit and greatest discrimination for the chinchilla impulse noise exposures (Hamernik et al., 1998). The L_{Aeq8} affords the best sensitivity and specificity for discrimination of potential hazards and has the greatest level of integration with present occupational exposure standards and prospective hearing protection labeling regulations.

List of Abbreviations and Acronyms

Symbol	Description	Page
AHAAH	Auditory Hazard Assessment Algorithm for Human	1
AHU	Auditory Hazard Units	12
ANSI	American National Standards Institute	3
ATF	Acoustic Test Fixture	8
BOP	Albuquerque Blast Overpressure Study	8
CHABA	Committee on Hearing, Bioacoustics, and Biomechanics	1
CTS	Compound Threshold Shift	14
dB SPL	decibels Sound Pressure Level	2
DRC	Damage Risk Criterion	1
EPA	U.S. Environmental Protection Agency	6
EU	European Union	6
IEC	International Electrotechnical Commission	6
IPIL	Impulse Peak Insertion Loss	9
ISL	French German Research Institute de Saint Louis	17
ISO	Institute for Standardization Organization	6
L_{Aeq8}	8-hour A-weighted Equivalent Energy	1
L_{peak}	Peak Level	2
MEM	Middle-Ear Muscle	4
MIRE	Microphone-In-Real-Ear	8
NIOSH	National Institute for Occupational Safety and Health	6
OSHA	U.S. Occupational Safety and Health Administration	6
p_0	Reference pressure 20 micropascal	3
$p_A(t)$	A-weighted pressure time signal	6
PTS	Permanent Threshold Shift	12
QIC	Quasi-likelihood Information Criteria	10
REAT	Real Ear Attenuation at Threshold	8
SEL	Sound Exposure Level	3
T_C	C-duration	2
T_D	D-Duration	2
t_e	Acoustic energy decay time constant	3
TM	Tympanic Membrane	5
TTS,	Temporary Threshold Shift	2
USAARL	U.S. Army Aeromedical Research Laboratories	1
β	Kurtosis	7

1 Origins of Damage Risk Criteria

The effects of exposure to intense high-level short-duration (impulse) noise have long been known for its risk of producing hearing loss. The risk of hearing loss increases as the level increases from a hand clap, objects colliding, fireworks, small caliber weapons and progressively larger weapons. At peak levels above about 140 decibels sound pressure level (dB peak SPL) the risk of impairment due to a single exposure event is no longer negligible. That is, the sensory cells of the cochlea can suffer temporary dysfunction or be permanently destroyed. At levels above about 165 dB peak SPL, the unprotected ear will likely suffer an irrecoverable shift in hearing. Above 180 or 185 dB peak SPL, the unprotected ear has a significant risk of permanent hearing loss and possibly rupturing the tympanic membrane. As levels increase beyond 185, the risks shift from not just the auditory impairment, but also risks to air-filled organs of the body: when the oral, nasal and pharyngeal cavities, lungs, stomach and intestines can hemorrhage. As the lethality of weapons systems increase, the risk to the war fighter in close proximity to the weapon discharge tends to increase.

The US Army Medical Research and Materiel Command has recently renewed the effort to update the damage risk criteria (DRC) for estimating safe levels of exposure for war fighters that train and use these systems in battle. This paper is a review of several damage risk criteria for impulse noise exposure and a summary of the analyses of two exposure studies: the Albuquerque Blast Overpressure Walk-up Study (BOP) and the Chinchilla impulse noise exposure studies from the US Army Aeromedical Research Laboratories (USAARL). In particular the DRCs that will be discussed below are the MIL-STD 1474D, Pfander, Smoorenburg, 8-hour A-weighted equivalent energy (L_{Aeq8}) and the Auditory Hazard Assessment Algorithm for Human (AHAAH) cochlear model.

1.1 Waveform Parameter-based DRC

In the mid 1960's, researchers established damage risk criteria for hearing loss due to impulse noise exposure (Coles et al., 1967; Ward, 1968). Coles et al. (1967) identified several parameters of a single impulse waveform that would be useful for rating the relative risk of hearing loss: peak pressure level, rise time, initial overpressure duration (A-duration), pressure envelope duration (B-duration), and frequency spectrum. The National Academy of Sciences National Research Council Committee on Hearing, Bioacoustics, and Biomechanics (CHABA) established the first damage-risk criterion (DRC) in the United States (Kryter et al., 1966; Ward 1968). The CHABA proposal was incorporated into the MIL-STD 1474 Noise Limit Design Criteria.

1.1.1. MIL-STD 1474D

MIL-STD 1474D (1997) does not allow unprotected exposure to SPLs greater than 140 dB SPL (W-Curve), regardless of A or B duration. The X-curve purports to estimate the protection afforded for wearing single hearing protection (earplugs or earmuffs). The Y-curve purportedly estimates the risk curve for wearing double hearing protection (earplugs and earmuffs). At the Z-Curve level of 180 to 190 dB and above, impulse pressures are sufficient to damage air-filled organs within the body such as the lungs, larynx, or gut. To account for the use of a single hearing protector, the equal risk contour was shifted upward by 29 dB[1]. The Y-curve is shifted by 6.5 dB for double protection relative to the X-curve. This shift is appropriate when considering continuous noise exposures. However for impulse noise, depending upon the particular details of an exposure, the protection afforded by an earmuff and earplug could be substantially greater (Murphy and Tubbs, 2007; Murphy et al., 2007, 2011, 2012}

1.1.2. Pfander

Pfander et al., (1980) and Smoorenburg (1982) proposed variants of the CHABA criteria utilizing different durations and accumulation of risk due to multiple impulses. The Pfander effective exposure level, L_P, is calculated as follows:

$$L_P = L_{peak} + 10 \log T_C + 10 \log N, \qquad (1)$$

where L_{peak} is the peak pressure, and T_C is the C-duration (the integrated time in milliseconds where the absolute amplitude of the waveform is within 10 dB of the peak pressure) and the trading ratio for impulses is 10 log(N).

1.1.3. Smoorenburg

Smoorenburg (1982) proposed a nearly identical form

$$L_S = L_{peak} + 10 \log T_D + 10 \log(N), \qquad (2)$$

where L_{peak} is the peak pressure and N is the number of impulses. However, T_D is the D-duration and describes the time in milliseconds during which the envelope of the waveform stays within 10 dB of the peak pressure.

Neither, Pfander's nor Smoorenburg's damage risk criteria account for the spectral effects produced by impulses from different sources, impulses filtered by the ear, and impulses filtered by hearing protection. For impulsive noise exposures, the peak sound pressure level, the number of impulses, the spectrum of the impulse and the duration of the exposure are the dominant factors for estimating the risk of hearing loss. Presumably, the measured sound pressure level underneath the

[1] Garinther and Hodge (1971) conducted a Temporary Threshold Shift (TTS) study with soldiers firing a shoulder-mounted rocket and identified about 25-dB protection for the V-51R earplug. A typical foam earplug has a Noise Reduction Rating of 29 dB.

protector would serve as the L_{peak}. For the Albuquerque blast overpressure walk-up study, (Chan et al., 2001) evaluated the Pfander, Smoorenburg and MIL-STD 1474D DRCs metrics for impulses measured outside the hearing protector and found them to be inferior to the L_{Aeq8} DRC based on 8-hour equivalent A-weighted energy. Furthermore, Chan did not report results evaluating the exposures underneath the hearing protectors; however, other researchers included protected exposures in subsequent analyses (Price 2007b; Murphy et al., 2009).

1.2 Equivalent-energy DRC

The first formulation of an A-weighted acoustic energy criterion was developed by Atherley and Martin (1971). They assumed that an impulse or series of impulses were experienced in a reverberant environment. Starting from the intensity of a sinusoidal signal that decays exponentially, their derivation resulted in the following equation,

$$\begin{aligned} L_{eq} &= 10\,\log\left(n\,t_e p_h^2 (1 - e^{-\frac{2}{t_e N}})/4p_0^2\right) \\ &= 88 + 20\log(p_h) + 10\log(N) + 10\log(t_e) + 10\log(1 - e^{-\frac{2}{t_e N}}), \qquad (3) \end{aligned}$$

where p_h is the peak amplitude in Pascals (N/m^2), N is the repetition rate in seconds, and t_e is the time constant for the decay of acoustic energy. The first two terms yield the sound pressure level when p_0 = 20 μPa,

$$L_{peak} = 88 + 20\log p_h = 20\log\left(\frac{p_h}{p_0}\right). \qquad (4)$$

Atherley and Martin applied a -2.6 dB correction factor to compensate for the difference between the use of linear and an A-weighting filter.

Stevin et al., (1982) examined several impulses using the sound exposure level (SEL) that translates the energy to an equivalent one-second exposure. Stevin concluded that the A-weighted SEL was a reasonable DRC for sound pressures up to about 170 dB SPL or exposure levels of 135 dB SEL. The one-second exposure can be adjusted for a total 8-hour equivalent exposure by 10 log(1/28800) = -44.6 dB, which yields about 90.4 dB for a daily 8-hour exposure. Dancer et al., (1995) compared two classical DRCs and arrived at a similar conclusion for a potential threshold limit value of L_{Aeq8} = 85 dB.

The L_{Aeq8} criterion is based upon filtering the acoustic signal to approximate the transfer function of the auditory periphery and integrating its energy. The A-weighting curve is derived from the iso-loudness curve at 40 phons and it is implemented into most sound measurement instruments in use today (ANSI S1.4-

2006). The attractiveness of the L_{Aeq8} approach is its simplicity and ability to integrate both continuous and impulsive noise. Firing of multiple weapons in either an open space or a reverberant environment does not present a complication for the acoustic analysis. Firing weapons in a reverberant environment versus an outdoors environment and incurring multiple exposures with or without a rest period result in different amounts of hearing loss for animal models and presumably humans (Kryter 1966; Chan et al., 2001; Price, 2004; Patterson and Ahroon, 2005).

1.3 Model-based DRCs

The use of a filter-based approach to account for the transmission characteristics of the human ear has its limitations. For instance, at the extreme sound pressure levels, the acoustics become nonlinear above about 140 dB SPL. Price and Kalb (1991) proposed an electroacoustic model of the outer and middle ear to derive the stapes displacement. Using the stapes displacement, the WKB (Wentzel-Kramers-Brillouin) solution is used to determine the response of the basilar membrane (BM) at 23 locations[2]. The Auditory Hazard Assessment Algorithm for Human (AHAAH) model incorporates several unique features not typically found in other cochlear models. Whereas most cochlear models are concerned with modeling the traveling wave along the basilar membrane at low to moderate input levels, the AHAAH model is concerned with high-level inputs. Typical cochlear models have a nonlinear cochlea and a linear outer and middle ear; the AHAAH model has a linear cochlea and a nonlinear middle ear. Above 130 dB SPL, the annular ligament limits the displacement of the stapes footplate to about 20 μm and the basilar membrane's nonlinear amplitude response saturates above 80 to 90 dB SPL. Transmission of sound through the outer ear is assumed to be linear since the electroacoustic circuit of the AHAAH does not incorporate any simulation of the viscoelastic effects of air at high sound pressure levels. The AHAAH model implements the middle ear muscle reflex as a time-dependent impedance gain controller (Price 2005, 2007b; Song, 2010) in response to high-level stimuli. The middle-ear muscle (MEM) reflex is activated in response to a signal that exceeds a given threshold of about 108 dB (unwarned condition). Alternatively, the model allows the MEM to already be active and therefore in a state of reduced transmission (warned condition). The AHAAH model does not include the reflex decay following an impulse; neither does it include fatigue of the response.

Song (2010) evaluated seven middle ear models, including the AHAAH middle ear, and discussed several limitations. First, one-dimensional network models such as the AHAAH model can only describe the translational motion of the stapes. Two and three-dimensional models can simulate the pumping and rocking modes that

[2] Note that Price and Kalb (1991) reported using 512 locations. However, the current AHAAH model reports 23 sites spaced along the basilar membrane.

are prevalent when the stapedius muscle is contracted and limiting the stapes motion. Second, the response of the tympanic membrane (TM) will be limited due to the changes in modal response as frequency increases. The TM model is frequency-limited to about 4 to 6 kHz. Third, the nonlinear acoustics within the ear canal and middle ear cavities are ignored within the network model. Song noted that large differences across the various cochlear models implied the utility of the model-based approach was limited to qualitative rather than an absolute simulation of the cochlear response.

2 Damage Risk Criterion

For the person exposed to impulsive sound, the peak pressure level, spectrum, number of events, and physical environment must be considered when determining the risk of incurring hearing loss. The L_{Aeq8} damage risk criterion explicitly incorporates the peak pressure level by integrating the energy of the exposure and the number of impulse events by a multiplicative term, *N*. The spectrum of the impulse and physical environment are not explicitly included as parameters in the L_{Aeq8} computation. However, the auditory periphery filters the exposure and the A-weighting filter applied in L_{Aeq8} accounts for that effect. Reverberation caused by the physical environment can be implicitly included in the recorded exposure waveforms. The integrated energy for the reverberant environment will be greater than the integrated energy in a non-reverberant environment for the same weapon being fired (Jokel 2010; Murphy, 2010)

2.1 Definition of Equivalent Energy

Subsequent proposal for using L_{Aeq8} as a damage risk criterion arrives at a different formulation of Equation (3). Instantaneous sound pressure level is expressed in decibels,

$$\text{dB SPL} = \mathbf{20\ log}{}^{\boldsymbol{p}}/_{\boldsymbol{p_0}}, \qquad (5)$$

where the reference pressure is $p_0 = 20\ \mu\text{Pa}$. The time-averaged squared acoustic sound pressure yields an equivalent level,

$$\boldsymbol{L_{eq,T}} = \mathbf{10\ log}\left(\frac{\mathbf{1}}{\boldsymbol{T}}\int_{\mathbf{0}}^{\boldsymbol{T}}\frac{\boldsymbol{p^2(t)}}{\boldsymbol{p_0^2}}\boldsymbol{dt}\right), \quad (6)$$

where *p(t)* is the sound pressure as a function of time and *T* is the averaging time. The above equation can also be given in terms of A-weighted sound level,

$$L_{Aeq,T} = 10\log\left(\frac{1}{T}\int_0^T \frac{p_A^2(t)}{p_0^2}\,dt\right), \quad (7)$$

where $p_A(t)$ is the A-weighted pressure signal as a function of time.

When a person experiences multiple impulse exposures from the same source without changing the physical environment or head location, the contributions can either be integrated over the entire time as in Eq. (6) or the average of the individual events can be determined and multiplied by the number of impulses as follows,

$$L_{Aeq,8hr} = 10\log\left(\frac{1}{t_1 - t_2}\int_{t_1}^{t_2} \frac{p_A^2(t)}{p_0^2}\,dt\right) + 10\log\frac{t_2 - t_1}{T_{8hr}} + 10\log N, \quad (8)$$

where $p_A(t)$ is the A-weighted pressure signal as a function of time, t_1 and t_2 define the duration of the impulsive event and N is the number of events. Setting the value of T_{8hr} = 28,800 normalizes the energy of the event whose duration is measured in seconds to the equivalent 8-hour exposure. In the case of averaging, the primary exposures are assumed to be distinctly separated.

2.2 Adherence to Acoustic Standards

ANSI S1.4-2006 defines the specification for sound level meters including the functions for C and A-weighting. The filters can be implemented as hardware filters as in a sound level meter, as digital filters in an analysis package or as spectral weighting corrections for use with octave band analysis. IEC 61672-1:2002 is the international standard for specifying performance criteria for sound level meters. For the measurement of occupational exposure to noise, the US standard, ANSI S3.44-2006, utilizes measurements conducted with A-weighting. The international standard for conducting an engineering grade survey of occupational noise exposure, ISO 9612:2009, requires A-weighted noise measurements and incorporates impulsive noise exposures. The French military has proposed the A-weighted equivalent exposure as a damage risk criterion for military noise exposures (DTAT 1983). The European Union (EU) has established peak exposure limits of about 140 dBC and daily equivalent exposure limits of 85 dBA (EU Directive 2003/10/EU, 2003).

2.3 Integration with Current Occupational Exposure Criteria

In 1972, NIOSH recommended an occupational exposure limit of 85 dBA time-weighted average and 5-dB exchange rate (NIOSH 1972). Around the same time period, the US Environmental Protection Agency (EPA) and the US Occupational Safety and Health Administration (OSHA) conducted independent risk assessments and arrived at exposure limits of 70 dBA for no excess risk of hearing loss and a permissible exposure level for workers of 90 dBA Time-Weighted Average (EPA 1973; EPA 1974; OSHA 1981). Subsequent analysis led to the NIOSH Revised Criteria Document for a Recommended Standard for Occupational Noise Exposure (NIOSH 1998). A quantitative limit was developed from the data collected in the Occupation Noise and Hearing Survey. Principally, the NIOSH levels were established through a logistic regression analysis completed by Prince et al. (1997). Using standard epidemiologic statistical methods, these analyses estimated the excess risk of developing material hearing loss for prolonged exposures to occupational noise over the course of ten to forty years.

The NIOSH analysis reports the percentage of workers that can be expected to suffer a material hearing impairment if different exposure criteria are selected. For instance, using the 85 dBA equivalent 8-hour TWA a worker is at an 8% excess risk of developing a 25-dB average hearing loss for both ears at 1000, 2000, 3000 and 4000 Hz after a forty year career working in noise. Selection of 90 dBA yields a 25% excess risk of material hearing impairment. NIOSH's analysis utilized a 3-dB exchange rate. Current U.S. and international occupational noise exposure standards use an 85 dBA limit for a recommended action level above which hearing protection should be worn (ANSI S3.44-2006; ISO 1999, 1990). Hearing protection is not required to be worn until the permissible exposure (90 dBA) is exceeded (OSHA, 1981). In the European Union, the 80 dBA is the established lower action limit (EU Parliament, 2008). More conservative hearing conservation programs might choose lower permissible exposure limits in line with EPA or NIOSH analyses (EPA, 1974; NIOSH, 1998).

One current problem that L_{Aeq8} faces is the integration of impulse and continuous noise exposures. Dunn et al. (1991) demonstrated that equal exposures of impulse or continuous noise resulted in greater magnitude of hearing loss in the group exposed to impulse noise. Hamernik and Qiu (2001) completed an exhaustive series of exposures of animals to equivalent energy doses but with different levels of kurtosis or peakedness of the acoustic signal. Animals exposed to noise having a lower kurtosis (β) value suffered less hearing loss. This topic is of particular importance for establishing guidelines to protect workers and war fighters against exposure to impulsive noise.

Recent work by Zhao et al. (2010) show that impulse exposures can be integrated with continuous noise exposure dose-response curves for humans. The significance of their work should not be underestimated. For occupational noise exposures with impulsive content, the rule of thumb is to add 5 dB to the continuous dose estimate to compensate for the increased risk (CSA Z94-2, 2002; Berger et al., 2003; Hall et al., 2005). Zhao demonstrated that the damage risk curves from ISO 1999 (1990) for workers exposed to continuous noise and impulse noise could be matched if the impulsive nature of the exposure were assessed using a kurtosis metric. L_{Aeq8} can be readily modified to incorporate a kurtosis factor. Thus the equivalent energy can be used for a single DRC for the entire range of exposures that are commonly found in military environments. Goley (2010) developed a modification of the L_{Aeq8} formulation using kurtosis for the occupational exposure and has applied this modification to the chinchilla exposure data base reported by Hamernik et al. (1998).

2.4 Hearing Protection within LAeq8

The L_{Aeq8} method can integrate measures of hearing protector effectiveness to modify the estimated exposure. Measurements using the acoustic test fixture (ATF) or Microphone-In-Real-Ear (MIRE) methods described in ANSI S12.42-2010 will prove useful to estimating actual performance of hearing protection. Octave band attenuation data provides one possible implementation of combining ATF measurements with exposure estimates (Parmentier et al., 2000; Murphy and Tubbs, 2007; Berger and Hamery, 2008). Murphy et al. (2009) evaluated the Albuquerque Blast Overpressure (BOP) study MIRE measurements measured under a leaky earmuff and demonstrated an equivalent protection of about 14 dB. Interestingly, the Real Ear Attenuation at Threshold (REAT) and MIRE measurements are typically performed at levels below 105 dB to prevent endangering human volunteers (ANSI S12.6-2008, ANSI S12.42-2010). The passive attenuation characteristics of hearing protection devices are assumed to be constant over the range of typical occupational exposure 85 to 140 dB SPL. Thus low-level measurements of attenuation apply for most protectors, so long as they don't have sound restoration, active noise cancellation or amplitude-sensitive characteristics.

Stevin (1982) evaluated several gunfire impulse exposures with the Sound Exposure Level (SEL) method for the unprotected condition and for the EP100 and cotton-wool earplugs. The allowed number of shots for the unprotected case was 5, whereas the EP100 yielded 5000 and the cotton-wool was 80 impulses. Murphy and Tubbs (2007) showed an earplug provided more peak impulse reduction than earmuffs when used as the only protector. The peak reduction for the impulse was nearly additive when evaluating a foam earplug and an earmuff. The MIL-STD 1474D criteria multiplies the allowable number of shots by a factor of 20 when double protection is used, thus increasing the exposure limit by 6.5 dB. For continuous noise exposures, 5 or 6 dB is the rule of thumb to account for the additional noise reduction afforded by wearing double protection. MIL-STD 1474D may grossly underestimate the improvement when wearing double protection because the peak levels are reduced significantly more than 6.5 dB when measured on an acoustic test fixture (Murphy and Tubbs, 2007; Murphy et al., 2011). The physical shape of an earmuff can interfere with shoulder-fired weapons causing the seal of the earmuff to be disrupted when aiming or firing a weapon. The protection factor depends upon the composition and design of the hearing protection device and how it interacts with additional protectors. Murphy and Tubbs (2007) reported a 15 to 18 dB reduction of the attenuation of a gunshot impulse due to wearing safety glasses that disrupt the seal of earmuff cushions. The effect of other personal protective equipment must be considered carefully before deployment into high-level impulse noise environments.

2.5 Hearing Protection within other Damage Risk Criteria

Dancer (1999) examined several aspects of hearing protection for the military environment. With respect to the performance of protectors in high-level impulse noise, the response is often nonlinear and difficult to predict (Zera and Mlynski, 2007; Berger and Hamery, 2008; Mlynski and Zera, 2008). For the L_{Aeq8} method, the exposure underneath the protector must be estimated. The one-third octave spectra can be measured for a variety of impulses using an acoustic test fixture and the resulting attenuations can be applied to other waveforms to estimate the protected exposures.

In MIL-STD 1474D, the hearing protection is a fixed protective factor of 29 dB for single protection and an additional 6.5 dB for double protection. As stated above, the 29 dB resulted from research conducted by Aberdeen Proving Ground with shoulder-fired rockets and the V-51R earplug (Garinther and Hodge, 1971). For the Pfander and Smoorenburg damage risk criteria, the protection could be implemented as a change in the peak pressure level measured under the protector and the change in the C and D durations between the field and the protected condition. Changes in the envelope may be more significant for earmuffs than for earplugs due to the low-pass nature of muffs. Earplugs tend to have a more uniform attenuation across frequencies resulting in a protected waveform that is recognizably an impulse, albeit at a lower level. The waveforms under earmuffs tend to exhibit the pumping response of the muff as it oscillates due to the impulse excitation (Zera and Mylnski, 2007; Mlynski and Zera2008). Mlynski and Zera (2008) found that the C duration could be better predicted than the D duration. The duration predictions were overestimated by about 10% to 80% of the values measured underneath the earmuff. The peak levels were accurate to within one to three decibels. Thus the accuracies of predictions for parameter-based damage risk criteria could be within several decibels of the *true* answer. Murphy et al. (2012) has recently reported the first set of measurements of Impulse Peak Insertion Loss (IPIL) made with the ANSI S12.42-2010 standard. These measurements demonstrated an increase in impulse peak insertion loss for all products with some devices exhibiting more than 15 dB increase in IPIL over the range from 130 to 170 dB peak SPL.

Recently, Kalb (2010) has developed a new modeling approach using a distributed element circuit model to estimate the performance of hearing protectors based upon the REAT measurements of a plug or muff. The model makes three general assumptions: 1) earmuff/plug moves as a rigid piston; 2) leakage occurs around the seal of the muff or plug; and 3) the muff/plug exhibits some amount of material deformation. These assumptions lead to a curve fit of the REAT data and an optimization of the parameters defined in the circuit model of the protector. Once the parameters are fit, the circuit is inserted into the AHAAH model for computation of the protected waveform. This method exhibits promise with regards to being able to independently evaluate the protected impulse response of any protector. Electronic devices may prove to be problematic since REAT measurements assess only the passive performance of a device.

Regardless, the performance of hearing protection devices will require significantly more research to validate the models and predictions. As more research is conducted with the ANSI S12.42-2010 standard, the modeling of impulses interacting with hearing protection will rapidly advance.

2.6 Recent studies evaluating LAeq8

2.6.1 Albuquerque Blast Overpressure Study

NIOSH evaluated the Albuquerque BOP walk-up study using several damage risk criteria for impulse noise exposures (Murphy et al., 2009). Chan et al. (2001) had considered the MIL-STD 1474D, Pfander, Smoorenburg and L_{Aeq8} damage risk criteria for the free-field impulses measured in the BOP study, but did not evaluate the AHAAH model. They did not report results for waveforms measured underneath the hearing protector. Murphy et al. (2009) used the waveforms as provided by USAARL and Aberdeen Proving Ground to conduct an independent assessment of the BOP results. Previous analyses made assumptions regarding the outcomes for the soldiers who participated in the study.

In the original BOP experimental design, each exposure cell was considered to be monotonically more hazardous as one progressed from lower to higher impulse levels and as the number of shots increased. The evaluation of the exposures using the AHAAH model suggested that the middle exposure levels for the 1 and 3 meter distances were more hazardous than those occurring at the higher levels. Unfortunately, the actual exposures did not populate the middle of the exposure matrix sufficiently to establish the veracity of this prediction. In the NIOSH analysis, only the cells where exposures were conducted were used to establish the dose-response relationship. No assumptions were made about outcomes based upon persons who passed or failed at other levels. NIOSH's analysis sought to verify the 95% confidence interval for the logistic regression for the 5% most sensitive person, $L_{95,95}$ (Murphy et al., 2009).

Murphy et al. (2009) found that the unprotected L_{Aeq8} provided the best fit of the BOP data (See Table 1.). The other metrics had progressively poorer fitting performance as measured by the Quasi-likelihood Information Criteria (QIC) (Pan, 2001) in the following order: unprotected MIL-STD 1474D, unwarned AHAAH, protected L_{Aeq8}, and warned AHAAH models for the protected waveforms. The L_{Aeq8} damage risk criteria best characterized the increased risk of hearing loss as the impulse levels increased. $L_{95,95}$ represented the limits for possible damage risk thresholds relative to the exposures which were evaluated. Murphy et al. (2009) used both the audiometric failures (25-dB TTS) to estimate $L_{95,95}$ and the audiometric and conditional failures (15-dB TTS) as a more conservative estimate of damage risk threshold. If one determines that a 25-dB temporary threshold shift is the appropriate criterion figure of merit, then the limit values from that analysis should be used. If a 15-dB TTS is more important, then those values should be used. The $L_{95,95}$ damage risk thresholds reported by NIOSH and Chan et al. (2001), agree to within a few tenths of a decibel for the MIL-STD and the L_{Aeq8} free-field results when no propagation of failure was assumed. The NIOSH analysis using audiometric and conditional failures and no propagation of failure agreed with Chan's $L_{95,95}$ results that assumed propagation of failure within 3 dB for MIL-STD 1474D and within 0.5 dB for the L_{Aeq8} damage risk criterion (See Table 2).

Table 1. Goodness-of-fit Quasi-likelihood Information Criteria (QIC) scores for five damage risk criteria used with the Albuquerque Blast Overpressure Walk-up Study. Lower QIC scores indicate a better fit to the data.

Damage Risk Criterion	Goodness-of-Fit QIC Scores	
	Audiometric Failures	Audiometric and Conditional Failures
L_{Aeq8} Unprotected	273.73	630.26
MIL-STD 1474D Unprotected	282.01	636.25
Unwarned AHAAH Protected	304.51	650.85
L_{Aeq8} Protected	305.80	650.05
Warned AHAAH Protected	307.13	653.99

Table 2. Estimates of $L_{95,95}$ for five damage risk criteria used with the Albuquerque Blast Overpressure Walk-up Study from the Murphy et al. (2009). Audiometric failures were for participants that experienced a temporary threshold shift of 25 dB or more. Audiometric and conditional failures were for participants that experienced at least 15 dB TTS.

Damage Risk Criterion	$L_{95,95}$ Exposure Thresholds	
	Audiometric Failures	Audiometric and Conditional Failures
MIL-STD 1474D Unprotected	193.5 dB	185.1 dB
L_{Aeq8} Unprotected	123.6 dBA	115.4 dBA
L_{Aeq8} Protected	109.5 dBA	101.4 dBA
Unwarned AHAAH Protected	10108.7 AHU	3053.6 AHU
Warned AHAAH Protected	2479.8 AHU	718.7 AHU

One of the primary purposes for the Army to conduct the BOP study was to establish critical exposure levels for impulse exposures of war fighters. The MIL-

STD 1474D limits were developed by CHABA (Kryter, 1966; Ward, 1968). Occupational exposure limits for continuous noise were established by analyses of exposure databases (Burns and Robinson, 1970; Passchier-Vermeer, 1968; Prince et al., 1997). For the AHAAH model in cats, exposures of more than 500 Auditory Hazard Units (AHU) resulted in permanent threshold shifts of 25 dB or more. The AHAAH model for humans was created by transforming the cat model to fit human physiologic and acoustic data (Price, 1991; Price 2007a). In the NIOSH analysis, the human TTS data were used to determine the $L_{95,95}$ critical exposure levels from the 1, 3 and 5 meter blast overpressure data (See Table 2). For the warned and unwarned AHAAH models, the critical exposure levels are significantly greater than 500 AHU (Murphy et al., 2009).

In addition to the dose-response analysis, Murphy et al. (2009) analyzed the sensitivity and specificity of the different damage risk criteria. Price (2007b) reported a 2x2 contingency table analysis of the BOP data. Essentially, his analysis is one point along the curves which Murphy et al. (2009) tested for discrimination. Price predicted safe and unsafe exposures for the BOP study by evaluating exposure outcomes assuming critical exposure limits of 500 AHU for AHAAH, 85 dBA for L_{Aeq8} and 177 dB for MIL-STD 1474D. He concluded that the AHAAH model yielded 94% accuracy. If a different exposure limit is used for L_{Aeq8}, then the same exposures can be identified as safe and hazardous as what Price reported for the AHAAH model. Murphy et al. (2009) considered the range of possible exposure limits in conducting the sensitivity analysis and then evaluated the area under the curve (AUC) for whether the different metrics do a better job of discriminating whether a participant suffered a temporary threshold shift. In this sensitivity analysis, the L_{Aeq8} exhibited better sensitivity and specificity than the other metrics.

2.6.2 Chinchilla Blast Overpressure Data Evaluation

Murphy et al. (2010) applied the goodness-of-fit and discrimination analysis to the chinchilla impulse exposure data previously reported by Hamernik et al. (1998) and Patterson et al., (1993). The chinchilla data had temporary and permanent threshold shifts (PTS) in decibels at several frequencies and could be analyzed assuming a continuous variable. In contrast, only categorical 15 and 25-dB temporary threshold shifts were considered for the human data from the BOP study. The rank orders of the goodness-of-fit analyses for the continuous and categorical evaluations of the permanent and temporary threshold shift data from Murphy et al. (2010) are presented in Table 3 for five damage risk criteria models: L_{Aeq8}, Pfander, Smoorenburg, AHAAH and

Table 3. The ranking of goodness-of-fit for damage risk criteria applied to the Chinchilla impulse noise exposure data.

Damage Risk Criteria	PTS_{25}	PTS_{15}	PTS_{dB}	TTS_{25}	TTS_{15}	TTS_{dB}
LAeq8	1	1	1	1	1	1

Pfander	2	2	2	2	2	2
Smoorenburg	3	3	4	3	3	3
AHAAH Unwarned	4	4	2	5	4	5
AHAAH Warned	6	5	5	6	6	6
MIL-STD 1474D	5	6	6	4	5	4

MIL-STD 1474D. In all cases, the L_{Aeq8} damage risk criteria exhibited the best goodness-of-fit followed by the Pfander model. The warned AHAAH and MIL-STD 1474D were consistently ranked the poorest.

The discrimination analysis for the predictive performance of the different damage risk criteria was performed using the categorical variables of 15 and 25-dB permanent and temporary threshold shifts (See Table 4). The unwarned AHAAH model performed significantly better than the other damage risk criteria for the permanent threshold shift data. L_{Aeq8} exhibited better discrimination than the other damage risk criteria for the temporary threshold shift data. The AHAAH model's better discrimination for the PTS data than the TTS data could result from its attempt to estimate mechanical failure of the basilar membrane. The L_{Aeq8} damage risk criterion was not significantly different from the warned AHAAH model for either the PTS or TTS discrimination analysis.

Table 4. The ranking of discrimination analysis applied to the Chinchilla impulse noise exposure data.

Damage Risk Criteria	PTS_{25}	PTS_{15}	TTS_{25}	TTS_{15}
AHAAH Unwarned	1	1	2	2
L_{Aeq8}	3	3	1	1
AHAAH Warned	2	2	3	3
Pfander	4	5	5	5
Smoorenburg	5	4	4	4
MIL-STD 1474D	6	6	6	6

In addition to the goodness-of-fit and discrimination analyses, a linearized logistic function was fit to the threshold shift data and the correlation coefficient was determined at each frequency[3]. For the chinchilla analysis, the L_{Aeq8} exhibited the best correlation for both the temporary and permanent threshold shift data. The other models performed poorly with regards to the regression and correlation analyses. For the PTS data, the L_{Aeq8} correlations were overall rather poor, r^2 ~0.2 and for the TTS data correlations were somewhat better r^2 ~0.4. For this study, the evidence is clear that an equivalent energy approach was superior to the peak

[3] Using the logistic function yields slightly better correlations, but nonlinear regression procedures can depend heavily on the starting parameters leading to some difficulty in interpreting the r^2 values.

amplitude and duration utilized by the MIL-STD 1474D, Pfander and Smoorenburg models (Murphy et al., 2010).

Hamernik et al. (1998) reported correlations for the chinchilla data of ~0.95 or better when summary statistics (percentiles, median and mean) were used and exposure metrics were binned into 5-dB steps. Similarly, Price (2007a) used a mean of the threshold shifts for different groups of cats to generate the regression between permanent threshold shift and compound threshold shift (CTS) data and between AHUs and CTS data. The various analyses of summary data yield conflicting claims regarding the superiority of one damage risk criteria versus another. Therefore, the NIOSH results are significant because the same analyses were used to compare the various damage risk criteria (Murphy et al., 2010).

3 Future Research for the L_{Aeq8} and other Damage Risk Criteria

In the previous section, several shortcomings have been identified and discussed: Intermittent exposures, middle-ear nonlinearities, integration with traditional damage risk criteria, accounting for hearing protection devices and the effects of secondary exposures. Each of these topics presents fruitful areas for future research that will be explored in this section.

3.1 Intermittency of Exposure

MIL-STD 1474D and other parameter-based DRCs do not allow adjustment for the intermittency of exposure. For the L_{Aeq8}, intermittency is essentially dealt with in a simple manner: the energy from one exposure can be added directly to another exposure. ISO 9612:2009 standard details one method for combining task-based and area-based exposures. If the goal of the revision for MIL-STD 1474D is to have a more comprehensive evaluation of a warfighter's exposure, then the contribution of non-impulsive exposures must be considered.

Intermittency is a particular problem for the AHAAH model. The AHAAH model analyzes both the warned and the unwarned conditions so that one can judge the effect of pre-activation of the MEM reflex. The MEM reflex can be activated in the AHAAH model but cannot be turned off. The model assumes that once a threshold is exceeded, that the MEM reflex will be activated and will reach full strength in about 200 msec. In reality, the MEM reflex can be activated and released; it may not reach full activation for some impulses; it may be completely absent in some persons. In a report evaluating impulsive exposures at three manufacturing plants, the assessment of the AHAAH model with continuous noises exhibited estimates of exposure that would suggest that workers not wearing hearing protection would suffer profound hearing losses: PTS > 100 dB for a 10000 AHU exposure

(Vipperman et al., 2006). The AHAAH analysis for the warned and unwarned condition showed no difference for waveforms of 10 to 30 seconds in duration. In essence, the MEM reflex was fully activated by about 200 msec after the start of the sample and never turned off. To analyze extended noise exposures with intermittent impulse events, the AHAAH model allows the MEM reflex to activate, release and simulate fatigue of the muscular reflex. The occupational exposures in Vipperman et al. (2006) are not isolated examples of poor predictions by the AHAAH model. In several presentations, Price has noted that the hearing loss resulting from a referee's whistle will produce a 57-dB permanent hearing loss for a person standing 1 meter in front of the whistle (Price, 2007c). While there may be many blind referees on the field of play, if this prediction were true, deafness amongst athletes would exist in epidemic proportions.

The most equitable approach to allow for the range of responses for the MEM reflex would be to assume the worst case and omit it from the damage risk criteria. Furthermore, the role of the efferent system is not well-known with regards to impulse exposures may prove to be a significant omission from all of the damage risk criteria. Since the 1990s, sound conditioning prior to, and following a traumatic noise exposure has demonstrated protection against noise induced hearing loss (Yonovitz, 1976; Kujawa and Liberman, 1997; LePrell et al., 2003). Integrating the continuous exposures with impulse exposures is a significant feature omitted by the AHAAH model and included in the L_{Aeq8} damage risk criterion.

3.2 Effects of Middle-Ear Nonlinearities

This topic is perhaps the one which needs the greatest amount of research. From the work that Price has conducted with cats, the data indicate that the potential for nonlinear effects are significant. The limitation of the stapes displacement is a real effect and should be accounted for in a damage risk criterion. The experiments by Hamernik and Patterson with chinchillas may not have tested the limit of the stapes displacement. Price's exposures of cats to howitzer and airbag impulses may have done so. Price and Kalb (1999) sought to test this hypothesis with cats by sealing the passenger compartment of an automobile and producing an overpressure with an airbag discharge. His data suggest that windows open were more hazardous than windows closed and windows closed and compartment sealed. The differences were not statistically significant and therefore additional data need to be collected to resolve this effect. Similarly other exposures could be conducted with actual weapons. The wealth of exposure data for chinchilla should be a significant factor in deciding which animal model to choose. While the cat data might be available in some form, the chinchilla data have all the thresholds and the waveforms as well as histology results already assembled in a database.

3.3 Warned/Unwarned Hypothesis

In Price's analysis of the BOP study, the participants are assumed to be exposed under the warned hypothesis. They were given a countdown before each impulse and therefore were assumed to have activated an involuntary reflex through a conditioned response. In Murphy et al. (2009), several contradictory studies were cited that call into question the validity of assuming the warned state (Marshall et al., 1975; Bates et al., 1970; Fletcher and Riopelle, 1960). Whether or not these studies are conclusive, a shooter/spotter study with real weapons has been proposed to evaluate the status of the MEM reflex during shooting. A laboratory experiment along the lines of Bates et al. (1970) for preconditioning the MEM reflex could be repeated and conducted in a more rigorous manner.

The data from Marshall, Bates and Fletcher are published results, but hardly constitute a sufficient sample size on which to argue that all persons preparing to fire a weapon will involuntarily activate the MEM reflex. Rather, the fact that significant percentages of persons in those three studies *did not* exhibit the conditioned MEM reflex should be sufficient cause to reject the warned hypothesis as the proper mode to analyze every impulse. In the National Health and Nutrition Examination Survey 1999-2010, the acoustic reflex was assessed on more than 10,000 persons at 1000 and 2000 Hz. The National Center for Health Statistics has not released the data, as they have not determined how to code the results[4]. The prevalence of acoustic reflex could be determined for normal hearing persons who have not been exposed to occupational noise. In addition to prevalence, the strength and duration (fatigue) of a reflex with the amount of the protection must be quantified to fully account for MEM reflex in a damage risk criterion.

3.4 Integration with Traditional Risk Criteria

When we consider the integration of the impulse noise dosimetry problem, it becomes painfully evident that there is no mechanism within the waveform parameter-based models or the AHAAH model to combine impulse exposures with traditional methods to assess risk. AHUs are not decibels of equivalent energy and neither are the decibels estimated in the parameter-based models compatible with current dose-response metrics. Only the L_{Aeq8} method will integrate the continuous noise with impulsive noise. The problem that has been raised for assessing risk with animal exposures is that impulse noise has been demonstrated to be more hazardous. Fortunately, Hamernik's efforts over several decades has demonstrated a simple solution to the problem: adjust the exposure for kurtosis. In particular, the chinchilla research demonstrates that the effect of kurtosis exhibits a plateau once a level of about β = 50 is reached (Hamernik et al., 1998; Hamernik and Qiu, 2001; Hamernik et al., 2003). Furthermore, kurtosis has been applied to modify

[4] Personal communication with Dr. Howard J. Hoffman, National Institute on Deafness and other Communication Disorders, October 13, 2010.

impulsive occupational exposures and yields the dose response relations for humans (Zhao et al., 2010; Goley, 2010).

Further human research is needed. Dosimetry that captures warfighter's exposure from the beginning of a mission to the end of a mission needs to be collected. Audiometry must be collected and the waveforms for weapons discharge must be recorded. Only when a comprehensive database of this information is assembled will the scientific community move beyond arguing whether the BOP study was correctly analyzed and whether waveforms collected from old studies were valid. NIOSH is currently developing an impulse noise dosimeter capable of capturing levels that are occupationally relevant (< 170 dB peak SPL). The US Army should fund research to develop an impulse noise dosimeter capable of measuring blast over pressures to about 185 dB peak SPL. The technology exists to collect impulse noise exposure data for epidemiologic studies of from actual training and combat operations.

3.5 Integration of HPDs

The effort to integrate hearing protection into a damage risk criterion is preeminent. No one expects war fighters to commit to battle and remain effective if they have suffered a temporary or permanent threshold shift. Temporary threshold shifts are a liability to the mission; Permanent threshold shifts are detrimental to readiness and are a burden on the economy. The French German Research Institute de Saint Louis (ISL) has developed an anthropometric test fixture for testing hearing protection. The ISL fixture has been used since 1994 to develop the newest innovations for hearing protection to be used in the field of battle (Parmentier et al., 2000). Nonlinear acoustic valve earplugs are now standard issue for the US Army. These devices reduce the peak sound pressure level by about 20 dB at 130 dB to as much as 30 dB for 170 dB peak SPL (Berger and Hamery, 2008; Murphy et al., 2012).

With the development of the ANSI S12.42-2010 standard, a specification was developed for an acoustic test fixture suitable for evaluating hearing protection with high-level impulse noises. Two fixtures have been developed by ISL and G.R.A.S. Sound and Vibration. ISL has developed a mannequin with greater acoustic isolation than its previous fixture and heated ear canals. The G.R.A.S. 45CB fixture has simulated flesh-lined ear canals and integral heating controls. The ISL ear canals provide about 14 mm of usable insertion depth while the G.R.A.S. fixture has about 18 mm of insertion depth. Berger et al. (2011) demonstrated noise reduction measurements that were comparable to the REAT measurements for several premolded and formable earplugs and earmuffs with the G.R.A.S. 45CB fixture. Murphy et al. (2011) demonstrated agreement in the measurement of IPIL for premolded earplugs across three fixtures: unheated ISL fixture, heated ISL fixture and G.R.A.S. 45CB. For double protection, the G.R.A.S. 45CB exhibited about 10 to 20 dB less IPIL than the ISL heated and unheated fixtures. Future design iterations may yield better agreement in the performance between the two fixtures.

The problem of modeling performance of standard passive devices is not trivial. The early AHAAH model applied a minimum phase filter to estimate protected exposure. Patterson and Ahroon (2005) showed that the minimum phase model incorrectly estimated protected exposures when filtering the field exposures and comparing them against the protected exposures from the BOP study. A different approach uses a distributed element acoustic model fitting the REAT data with various curves to approximate a response under the protector (Paurobally and Pan, 2000; Zera and Mylinski, 2007). The Army Research Lab has applied both the minimum phase filter and distributed element methods to estimate the waveform under a hearing protector in response to high-level impulses (Kalb, 2010). The distributed element approach exhibits greater promise for accurate estimates of the protected exposure. A current NIOSH project will assess more than 30 hearing protection devices using the ANSI S12.42-2010 standard with an acoustic test fixture (Murphy et al., 2012). This project will develop and validate a theoretical acoustic model for use with impulses.

3.6 Effects of Secondary Exposure

Until recently, secondary noise exposure has largely been ignored. Flamme et al. (2011) have considered the effects for bystanders while small arms are fired. They measured a selection of rifles and shotguns at 1 meter to the left of the shooter and considered that to be a typical location for a bystander. Peak levels ranged from 149 to 166.5 dB SPL and the maximum permissible exposures ranged from 0 to 217 shots for the unprotected bystander. Although their analysis was not an exhaustive evaluation of the possible bystander locations and considered civilian firearms typically used in hunting and sport shooting, the methodology is of importance when attempting to account for the effects of secondary exposures. Is it sufficient to measure exposure at a few locations? Is it important to perform acoustic modeling to propagate the impulse measurement from one location to another?

Jokel (2010) has reported exposures measured at two indoor firing ranges with small-arms weapons. Several locations in the range were measured relative to the shooter's position. Particularly, the direct exposure for the shooter, exposures for shooters in other lanes and exposures for the range instructors were considered. When several persons are firing in an indoor range, the reverberant energy can accumulate to create continuous exposures in the 130 dB peak SPL range. Peaks from adjacent shooters follow the inverse-square law for the direct exposure. Reflections from surfaces will absorb some of the energy of the impulses. For instance, if a noise treatment is installed in the range, the reverberation times can be dramatically reduced which implies acoustic energy is being absorbed by the noise treatment. How one integrates the permissible exposures for the various damage risk criteria is not clear. For L_{Aeq8}, measurements can be combined with prediction of waveform propagation (see Rasmussen et al. (2009b) for an example of measurements around a weapon). Perhaps simple distance scaling (inverse square law) will suffice with a first or second order image-source model. Jokel (2010) evaluated direct, primary and secondary reflections and showed that the secondary reflections contributed minimally to the estimated dose. For the parameter-based DRCs, the addition of the secondary effects is unclear. The secondary reflections or impulses from other weapons would increase the B-duration if they fell within the amplitude envelope at the appropriate time. For the MIL-STD 1474D, the permissible exposure peak level is reduced as the B-duration increases.

For the AHAAH model, the secondary effects may be negligible or they could be highly significant. If one fires the weapon close to a wall, the reflection would be potentially higher than the initial peak and the separation of the direct and reflected peak could yield a worst case scenario where the reflection falls in the rarefaction trough of the direct impulse waveform. Such conditions would require extensive simulation to capture possible outcomes to estimate the range of hazards for the AHAAH model. The L_{Aeq8} approach could also undergo simulations for source locations relative to reflective surfaces. Conceivably the modeling for the L_{Aeq8} may be simpler than assessing hazards with the AHAAH model. Although with the increasingly more powerful computers, the additional step of running the AHAAH model may be negligible.

4 The Case for Selection of Equivalent A-weighted Energy

The L_{Aeq8} metric has several elements that point to why it should be selected for use as a damage risk criterion for evaluating both continuous and impulsive noise exposures. In the evaluations of the BOP study, the L_{Aeq8} demonstrated a better fit for the dose-response functions for the participants and the discrimination analysis was better than other metrics (Murphy et al., 2009). In evaluating the chinchilla exposures, L_{Aeq8} demonstrated greater predictive ability and better discrimination than the parameter-based metrics and the AHAAH method for the TTS data. The AHAAH metric showed slightly better predictive ability and discrimination for the PTS data. For the general correlation of a linearized logistic function with the TTS and PTS data, the L_{Aeq8} was superior to all the other models. While the AHAAH model purports to predict the response of the basilar membrane, the L_{Aeq8} third octave band analysis exhibited far less spread of the energy for the narrow-band stimuli compared to the AHAAH model. In general, the L_{Aeq8} was simpler to work with and provided excellent performance relative to the parameter-based metrics and was comparable to the AHAAH model (Murphy et al., 2010). The analyses conducted by Hamernik et al. (1998) and Hamernik and Qiu (2001) demonstrate that the regressions for predicting the mean and percentile performance for the chinchilla are superior to that observed for the cat data reported by Price (2007a). Although a direct cat-to-chinchilla exposure is not possible with the current data sets, the chinchilla could be exposed to impulses produced by rifles and howitzers to yield comparative data.

The L_{Aeq8} metric can be integrated immediately with the current damage risk criteria used with occupational hearing conservation metrics. Both American and international standards utilize L_{Aeq8}. Software and hardware implementations for standard filter functions and enhanced sensors will permit high-quality waveform capture to allow immediate analysis of impulsive events. Improved technology may soon provide extensive area assessments as well as personal impulse exposure monitoring in many environments.

The use of hearing protector models such as distributed element or even finite element methods to simulate the response of hearing protectors will improve our ability to estimate exposures. The L_{Aeq8} and the AHAAH model are based on physical acoustics and therefore can be used to predict protected responses. Hearing protector performance may be characterized with the methods contained within ANSI S12.42-2010.

For standardization, a simpler method has a greater likelihood of adoption in the field. Currently the AHAAH model exists in a few forms: the original Pascal code, a translated C-code version, a JAVA version and a SimuLink version. Only the SimuLink code has been developed independent of Price and Kalb (1991). For the AHAAH model to gain widespread acceptance and integration with instrumentation, the method will require validation independent of the originators of the model. Acoustic standards for sound level meters and dosimeters are based upon the L_{Aeq8} metrics.

The limitations that Price (2007b) and Price (2010) raised for L_{Aeq8} with regards to the middle-ear nonlinearities can be addressed with a modest amount of research. For instance, the large displacement of the stapes that Song (2010) noted for the transform approach could be modified by requiring a clipping function. While the AHAAH model already provides stapes clipping, the question remains whether exposures that produce such stapes clipping are safe and whether the MEM reflex is conditioned for all exposures and whether the reflex can be maintained for successive exposures. From the BOP study, parameter-based and L_{Aeq8} methods evaluate the higher-level exposures as more hazardous (Patterson and Johnson, 1994; Chan et al., 2001; Murphy et al., 2009)

The use of the L_{Aeq8} has been proposed as a standard for French armed forces (DTAT, 1983). The European Directive 2003/10/EU has been implemented in most of the European Countries but does not specifically apply to the military noise exposures (EU Parliament, 2008). Each state can create regulations for their own military. In the American National Standards Institute, work has commenced to develop an assessment standard that combines the waveform parameter-based models with the equivalent energy and the model-based metrics. Benchmark dose statistical models can combine multiple inputs from disparate assessments to determine potential safety.

Based upon the information reviewed in this report, the U.S. Department of Defense should use the L_{Aeq8} metric as the basis for changing the current MIL-STD 1474D.

5 References

46 Fed. Reg. 4078. [1981]. U.S. Department of Labor: Occupational Noise Exposure; Hearing Conservation Amendment; Final Rule. (Codified as 29 CFR 1910). Technical report, U.S. Department of Labor, Occupational Safety and Health Administration, Washington, DC.

ANSI S12.42. [2010]. American National Standard Methods for the Measurement of Insertion Loss of Hearing Protection Devices in Continuous or Impulsive Noise Using Microphone-in-Real-Ear or Acoustic Test Fixture Procedures. American National Standards Institute: New York.

ANSI S12.6 [2008]. American National Standard for the Measuring Real-ear Attenuation of Hearing Protectors. American National Standards Institute: New York.

ANSI S1.4-1983 (R2006) [2006]. American National Standard Specification for Sound Level Meter. American National Standards Institute: New York.

ANSI S3.44-1996 (R2006) [2006. American National Standard Method for Determination of Occupational Noise Exposure and Estimation of Noise-Induced Hearing Impairment. American National Standards Institute: New York.

Atherley GRC and Martin AM [1971]. Equivalent continuous noise level as a measure of injury from impact and impulse noise. Ann Occup Hyg, 14:11-23, 1971.

Bates MA, Loeb M, Smith RP, and Fletcher JL [1970]. Attempts to condition the acoustic reflex. J Aud Res, 10:132-135, 1970.

Berger EH and Hamery P [2008]. Empirical evaluation using impulse noise of level-dependency of passive earplug designs. In Acoustics `08, Paris, July 2008. Acoustical Society of America.

Berger EH, Kieper RW, and Gauger D [2003]. Hearing protection: Surpassing the limits to attenuation imposed by the bone-conduction pathways. J Acoust Soc Am, 114:1955-1967, 2003.

Berger EH, Kieper R, and Stergar M[2011]. Acoustical performance of two new acoustical test fixtures. In J Acoust Soc Am, San Diego CA, November 2011. Acoustical Society of America.

Burns W and Robinson DW [1970]. Technical report: Hearing and noise in industry. Her Majesty's Stationary Office:, London.

Chan PC, Ho KH, Kan KK, Stuhmiller JH, and Mayorga MA [2001]. Evaluation of impulse noise criteria using human volunteer data. J Acoust Soc Am, 110:1967-1975.

Coles RR, Garinther GR, Hodge DC, and Rice CG [1967]. U.S. Army Technical Memorandum 13-67 Criteria for Assessing Hearing Damage Risk from Impulse-Noise Exposure. Technical Report AMCMS Code 5011.11.84100, Human Engineering Laboratories, Aberdeen Proving Ground, MD, 1967.

CSA Z94-2 [2002]. CSA Standard Z94.2-02 Hearing Protection Devices - Performance, Selection Care and Use. Canadian Standards Association: Toronto, January edition.

Dancer A and Franke R [1995]. Hearing Hazard from Impulse Noise: A Comparative Study of Two Classical Criteria for Weapon Noises (Pfander Criterion and Smoorenburg Criterion) and the L_{Aeq8} Method. Acta Acustica, 3:539-547.

Dancer A, Buck K, Hamery P, and Parmentier G [1999]. Hearing protection in the military environment. Noise and Health, 5:1-15.

Direction Technique de Armements Terrestres [1983]. Recommendations on evaluating the possible harmful effects of noise on hearing. Technical Report AT-83/27/28, Establissement Technique de Bourges.

Dunn DE, Davis RR, Merry CJ, and Franks JR [1991]. Hearing loss in the chinchilla from impact and continuous noise exposure. J Acoust Soc Am, 90(4):1979-1985.

Environmental Protection Agency [1973]. Public health and welfare criteria for noise. Technical Report EPA Report No. 550/9-73-002, U.S. Environmental Protection Agency, Washington, DC.

Environmental Protection Agency [1974]. Information on levels of environmental noise requisite to protect public health and welfare with an adequate margin of safety. Technical Report EPA Report No. 550/9-74-004, U.S. Environmental Protection Agency, Washington, DC.

EU Parliament [2008]. Directive 2003/10/EC of the European Parliament and of the Council. Technical Report 2003/10/EC, European Parliament, 2008. Am., 114:1955-1967.

Flamme GA, Stewart M, Meinke DK, Lankford J, and Rasmussen P [2011]. Auditory risk to unprotected bystanders exposed to firearm noise. J Am Acad Aud, 22(2):93-103, 2011.

Fletcher JL and Riopelle AJ [1960]. Protective effect of the acoustic reflex for impulsive noises. J Acoust Soc Am, 32:401-404.

Garinther GR and Hodge DC [1971]. Small-Rocket Noise: Hazards to Hearing (Advanced LAW Program). Technical Report 7-71, Human Engineering Laboratories, May 1971.

Goley SG [2010]. Investigation and improvement of occupational and military noise exposure guidelines: Evaluation of existing and modified noise exposure metrics using historical animal data. Masters of Science, University of Cincinnati, May 2010.

Hall J, Mobley F, McKinley R, and Schley P [2005]. New directions for custom earplugs. In 2005 Conference and Exposition on Noise Control Engineering Rio de Janeiro, Brazil, page 89, Rio de Janeiro, Brazil, August 2005. I-INCE.

Hamernik RP and W. Qiu [2001]. Energy-independent factors influencing noise-induced hearing loss in the chinchilla model. J Acoust Soc Am, 110(6):3163-3168, December 2001.

Hamernik RP, Patterson JH Jr., and Ahroon WA [1998]. Use of animal test data in the development of a human auditory hazard criterion for impulse noise. Final

Report DAMD17-96-C-6007, State University of New York, Plattsburgh, NY, August 1998.

Hamernik RP, Qiu W, and Davis RI [2003]. The effects of the amplitude distribution of equal energy exposures on noise-induced hearing loss: The kurtosis metric. J Acoust Soc Am, 114:386-395, June 2003.

IEC 61672:1 [2002]. International Standard Electroacoustics - Sound level meters - Part 1: Specifications. International Electrotechnical Commission, Geneva.

ISO 1999 [1990]. Acoustics - Determination of occupational noise exposure and estimation of noise-induced hearing impairment. International Organization for Standardization, Geneva.

ISO 9612 [2009]. Acoustics - Determination of occupational noise exposure – Engineering method. International Organization for Standardization, Geneva, 2009.

Jokel C [2010]. Comparison of exposures at two indoor firing ranges. Draft Report, US Army Public Health Command.

Kalb JT [2010]. A hearing protector model for predicting impulsive noise hazard. In Proceedings of NOISE-CON 2010. U.S. Army Research Lab, April 2010.

Kryter KD, Ward WD, Miller JD, and Eldredge DH [1966]. Hazardous exposure to intermittent and steady-state noise. J Acoust Soc Am, 39:451-464.

Kujawa SG and Liberman MC [1997]. Conditioning-related protection from acoustic injury: Effects of chronic deefferentation and sham surgery. J NeuroPhys, 78:3095-3106.

LePrell CG, Dolan DF, Schacht J, Miller JM, Lomax MI, and Altschuler RA [2003]. Pathways for protection from noise induced hearing loss. Noise and Health, 5(20):1-17.

Marshall L, Brandt JF, and Marston LE [1975]. Anticipatory middle-ear reflex activity from noisy toys. J Speech Hear Dis, 40:320-326.

MIL-STD 1474D [1997]. Department of Defense Design Criteria Standard, Noise Limits. Department of Defense, Washington D.C.

Mlynski R and Zera J [2008]. Prediction of impulsive noise waveform under an earmuff worn by a real user. In Proceedings of Acoustics '08. Acoustical Society of America, July 2008.

Murphy WJ [2010]. Noise Mitigation at the Combat Arms Training Facility, Wright Patterson Air Force Base, Dayton OH. Technical report, National Institute for Occupational Safety and Health.

Murphy WJ and Tubbs RL [2007]. Assessment of noise exposure for indoor and outdoor firing ranges. J Occ Env Hyg, 4:688-697.

Murphy WJ, Byrne DC, and Franks JR [2007]. Firearms and hearing protection. Hear Rev, pages 36-38.

Murphy WJ, Khan A, and Shaw PB [2009]. An analysis of the blast overpressure study data comparing three exposure criteria. EPHB Survey Report 309-05h, National Institute for Occupational Safety and Health, Cincinnati, OH.

Murphy WJ, Khan A, and Shaw PB [2010]. An analysis of chinchilla temporary and permanent threshold shifts following impulsive noise exposure. EPHB Survey

Report 338-05c, National Institute for Occupational Safety and Health, Cincinnati, OH, October 2010.

Murphy WJ, Flamme GA, Sondergaard J, Meinke DK, Finan DS, Lankford JE, Khan A, and Stewart M [2011]. Comparison of three acoustic test fixtures for impulse peak insertion loss slides. In J Acoust Soc Am, San Diego CA, November 2011. Acoustical Society of America.

Murphy WJ, Flamme GA, Meinke DK, Sondergaard J, Finan DS, Lankford JE, Khan A, Vernon JA, and Stewart M [2012]. Measurement of impulse peak insertion loss for four hearing protection devices in field conditions. Int J Aud, 51: S31–S42.

NIOSH [1972]. Criteria for a Recommended Standard: Occupational Exposure to Noise. DHEW-CDC-NIOSH, Cincinnati, OH.

NIOSH [1998]. Criteria for a Recommended Standard - Occupational Noise Exposure Revised Criteria. DHHS-CDC-NIOSH, Cincinnati, OH.

Pan W [2001]. Akaike's information criterion in generalized estimating equations. Biometrics, 57:120-125.

Partmentier G, Dancer A, Buck K, Kronenberger g, and Beck C [2000]. Artificial Head (ATF) for Evaluation of Hearing Protectors. Acustica, 86:847-852.

Passchier-Vermeer W [1968]. Hearing Loss due to exposure to steady broadband noise. Technical Report No. 35 and Supplement to Report No. 35, Institute for Public Health Engineering, The Netherlands.

Patterson JH and Ahroon WA [2005]. Evaluation of an auditory hazard model using data from human volunteer studies. Technical Report USAARL 2005-01, U.S. Army Aeromedical Research Laboratories.

Patterson JH and Johnson DL [1994]. Temporary Threshold Shifts Produced by High Intensity Free-field Impulse Noise in Humans Wearing Hearing Protection. USAARL Report 94-46, U.S. Army Aeromedical Research Laboratories.

Patterson JH, Hamernik RP, Hargett CE, and Ahroon WA [1993]. An isohazard function for impulse noise. J Acoust Soc Am, 93(5):2860-2869.

Paurobally MR and Pan J [2000]. The mechanisms of passive ear defenders. Appl Acoust, 60:293-311, 2000.

Pfander F, Bongartz H, Brinkmann H, and Kietz H [1980]. Danger of auditory impairment from impulse noise: A comparative study of the CHABA damage-risk criteria and those of the Federal Republic of Germany. J Acoust Soc Am, 67:628-633.

Price GR [2004]. Firing recoilless weapons from enclosures. Scand Aud Suppl, 34 (39-48).

Price GR [2005]. A new method for rating hazard from intense sounds: Implications for hearing protection, speech intelligibility, and situational awareness. Technical Report NATO RTO-MP-HFM-123, NATO Research Technology Organization.

Price GR [2007a]. Predicting mechanical damage to the organ of Corti. Hear Res, 226:5-13.

Price GR [2007b]. Validation of the auditory hazard assessment algorithm for the human with impulse noise data. J Acoust Soc Am, 122:2786-2802.

Price GR [2007c]. Intense impulse noise: Hearing conservation's poison gas. In Proceedings of the 32nd Annual Hearing Conservation Conference, Savannah, GA, February 2007. National Hearing Conservation Association.

Price GR [2010]. Critique of “An Analysis of the Blast Overpressure Study Data Comparing Three Exposure Criteria,” by Murphy, Khan, and Shaw. Technical Report ARL-CR-657, Army Research Laboratory.

Price GR and Kalb JT [1991]. Insights into hazard from intense impulses from a mathematical model of the ear. J Acoust Soc Am, 90:219-227.

Price GR and Kalb JT [1999]. Auditory hazard from airbag noise exposure. J Acoust Soc Am, 106(5):2629-2637.

Prince MM, Stayner LS, Smith RJ, and Gilbert SJ [1997]. A re-examination of risk estimates from the NIOSH Occupational Noise and Hearing Survey (ONHS). J Acoust Soc Am, 101:950-963.

Rasmussen P, Flamme GA, Stewart M, Meinke D, and Lankford J [2009]. Measuring recreational firearm noise. Sound and Vibration, August.

Smoorenburg GF [1982]. Damage risk criteria for impulse noise. In Hamernik RP, D. Henderson, and R. Salvi, editors, New Perspectives on Noise-Induced Hearing Loss, pages 471-490, New York: Raven Press.

Song W-J[2010]. Study on Human Auditory System Models and Risk Assessment of Noise Induced Hearing Loss. Ph.D. Dissertation, University of Cincinnati, February 23 2010.

Stevin GO [1982]. Spectral analysis of impulse noise for hearing conservation purposes. J Acoust Soc Am, 72:1845-1854.

Vipperman J, Flamm A, Bradley M, and Hankinson S [2006]. Evaluation and characterization of exposure to impact noise for development of acoustical risk-damage parameters. NIOSH Contract Report 00HCC53-2005-19084, University of Pittsburgh, May 2006.

Ward WD [1968]. Proposed damage-risk criterion for impulse noise (gunfire). Technical Report Working Group 57, National Academy of Sciences - National Research Council, Committee on Hearing, Bioacoustics and Biomechanics.

Yonovitz A [1976]. Classical conditioning of the stapedius muscle. Acta Otolaryngol, 82:11-15.

Zera J and Mlynski R [2007]. Attenuation of high-level impulses by earmuffs. J Acoust Soc Am, 122:2082-2096.

Zhao Y-M, Qiu W, Zeng L, Chen S-S, Cheng X-R, Davis RI, and Hamernik RP [2010]. Application of the kurtosis statistic to the evaluation of the risk of hearing loss in workers exposed to high-level complex noise. Ear Hear, 31(4):527-532.

Delivering on the Nation's promise: Safety and health at work for all people through research and prevention.

To receive NIOSH documents or other information about occupational safety and health topics, contact NIOSH at

1-800-CDC-INFO (1-800-232-4636)

TTY: 1-888-232-6348

E-mail: cdcinfo@cdc.gov

or visit the NIOSH Web site at www.cdc.gov/niosh

For a monthly update on news at NIOSH, subscribe to NIOSH eNews by visiting www.cdc.gov/niosh/eNews

SAFER • HEALTHIER • PEOPLE