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# Energy Monotonicity and Positive Pressure Duration Dependence of Auditory Risk Unit Hazards

by Paul D Fedele and Mark A Ericson

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<b>14. ABSTRACT</b> Guidance on noise limits for Army materiel (per MIL-STD-1474E) describes two methods of assessing auditory hazards from exposure to impulsive waveforms: the Auditory Assessment Algorithm for Humans (AHA AH) and the A-weighted energy (AwE) method. Each method makes somewhat different hazard predictions for long positive-pressure-duration waveforms (such as those produced by large artillery muzzle blasts) and shorter positive-pressure-duration waveforms (such as those produced by rifle muzzle blasts), but the differences are not sufficiently large enough to establish consensus validity for either method when applied to muzzle blasts. However, hazard predictions differ far more significantly for extremely short positive-pressure-duration waveforms (such as the ballistic cracks produced by the passage of supersonic bullets). We assess the predicted hearing hazard for a series of waveforms with the same peak pressure and different time-dependencies to illustrate how the two different hearing hazard predictions change with waveform time-dependence while maintaining a constant peak pressure. We compare results of the methods, showing a range of positive pressure durations where AHAAH indicates increasing hazards, while AwE indicates decreasing hazards. Hazard observations for waveforms with positive pressure durations in this range will help resolve uncertainty in the validity of these two hazard assessment methods.						
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## Contents

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<b>List of Figures</b>	<b>iv</b>
<b>1. Introduction</b>	<b>1</b>
<b>2. Materials and Methods</b>	<b>1</b>
<b>3. Discussion</b>	<b>1</b>
<b>4. Conclusions</b>	<b>7</b>
<b>5. References</b>	<b>8</b>
<b>List of Symbols, Abbreviations, and Acronyms</b>	<b>10</b>
<b>Distribution List</b>	<b>11</b>

## List of Figures

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Fig. 1	AHAAH ARU values calculated for seven different waveforms with amplitudes adjusted to produce different AwE values for each waveform. (The waveforms are included as attachments to this technical note.).....	2
Fig. 2	A recorded ballistic crack and a simulated waveform with a PPD of 75 $\mu$ s.....	4
Fig. 3	Overlaid waveforms with various PPDs shown in microseconds in legend. (The waveforms are included as attachments to this technical note.).....	5
Fig. 4	Percent of allowable hazard for each hazard criterion: AwE-HAZ, AwE hazard percent; ARU(w)-HAZ, ARUs (Warned) hazard percent, ARU(uw)-HAZ, ARUs (Unwarned) hazard percent; and LAeq8hr-HAZ, LAeq8hr hazard percent .....	6

## 1. Introduction

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Guidance on noise limits for Army materiel, per MIL-STD-1474E (AMRDEC 2015), offers two different methods of assessment auditory risk. One method is based on the A-weighted energy (AwE) of the waveform and is a variant of the LAeq8 model (LIAeq100ms). It assesses hazard based on the time-averaged AwE of the impulse. The other assessment process is the Auditory Hazard Assessment Algorithm for Humans (AHA AH), which assesses hazard based on the maximum values of upward displacements of the basilar membrane (Price and Kalb 1991). Upward displacements are used because they apply tension to the tip-links on the stereocilia of the auditory hair cells, while downward basilar membrane displacements place hair cells in compression (Price and Kalb 2018).

## 2. Materials and Methods

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To illustrate the behaviors of the auditory hazard assessment methods described in MIL-STD-1474E, the AHA AH software was obtained from the US Army Research Laboratory: <https://www.arl.army.mil/www/default.cfm?page=343>. Following procedures detailed by Fedele et al. (2013), calculated values were obtained.

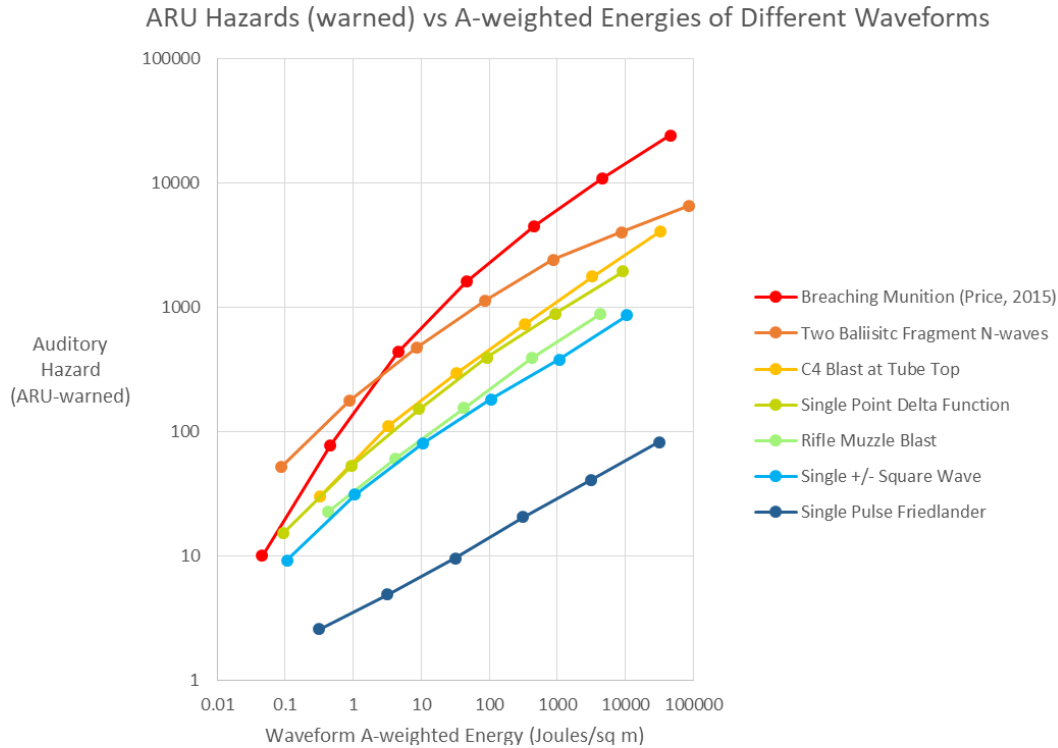
## 3. Discussion

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The AHA AH assessment has been called incorrect (Zagadou et al. 2016) because it can predict less hazard from a waveform with greater AwE than for a different waveform with less AwE (Price 2007b). Zagadou et al. (2016) attribute this behavior to presumed AHA AH errors regarding the nonlinear stapes compliance that AHA AH applies to stapes displacements. AHA AH's nonlinear stapes behavior produces a peak-clipped stapes displacement, and it does reduce energy transmission into the cochlea. Zagadou et al. (2016) indicate that AHA AH must be in error because they maintain that hazards must always be greater for waveforms with greater AwE.

While AHA AH's nonlinear stapes displacement does reduce energy transmission into the cochlea, more so than would a linear transmission process (Price 2007a), AHA AH still predicts more hazard when waveform amplitude increases *with no change in the time-dependence of the waveform* (i.e., amplitude changes only). Adjusting the calibration levels of seven different time-dependent waveforms, which are included as attachments to this technical note, AHA AH produces the following auditory risk unit (ARU) hazard predictions as a function of AwE, as shown in Fig. 1.



**Fig. 1 AHAH ARU values calculated for seven different waveforms with amplitudes adjusted to produce different AwE values for each waveform. (The waveforms are included as attachments to this technical note.)**

All waveforms used in this assessment are provided as attachments to this technical note. The attached waveform files are .AHA-type files. They are ASCII files in floating point format, which can be opened and read directly using Microsoft Notepad. They give the pressure in Pascal units, measurement timing information, and calculated waveform characteristics. They also can be opened directly by the AHAH software, although opening them with AHAH will require the recalculation of various calculated waveform characteristics, if the files are subsequently saved by AHAH.

In spite of very high pressure and energy levels in some of the waveforms, AHAH hazard predictions remain monotonic in energy. This is particularly demonstrated by the waveform consisting of a single-point approximation of a delta-function (yellow-green line), which has a positive pressure duration (PPD) of 2  $\mu$ s and a maximum pressure of 1200 KPa (216 dBp). Even though this pressure is very high, AHAH continues to predict increasing hazards as the waveform pressure and energy continue to increase.

Figure 1 also clearly demonstrates that waveforms with different time-dependencies and the same AwE can produce very different hazard levels. By applying a nonlinear displacement-dependent stapes compliance and basing hazard

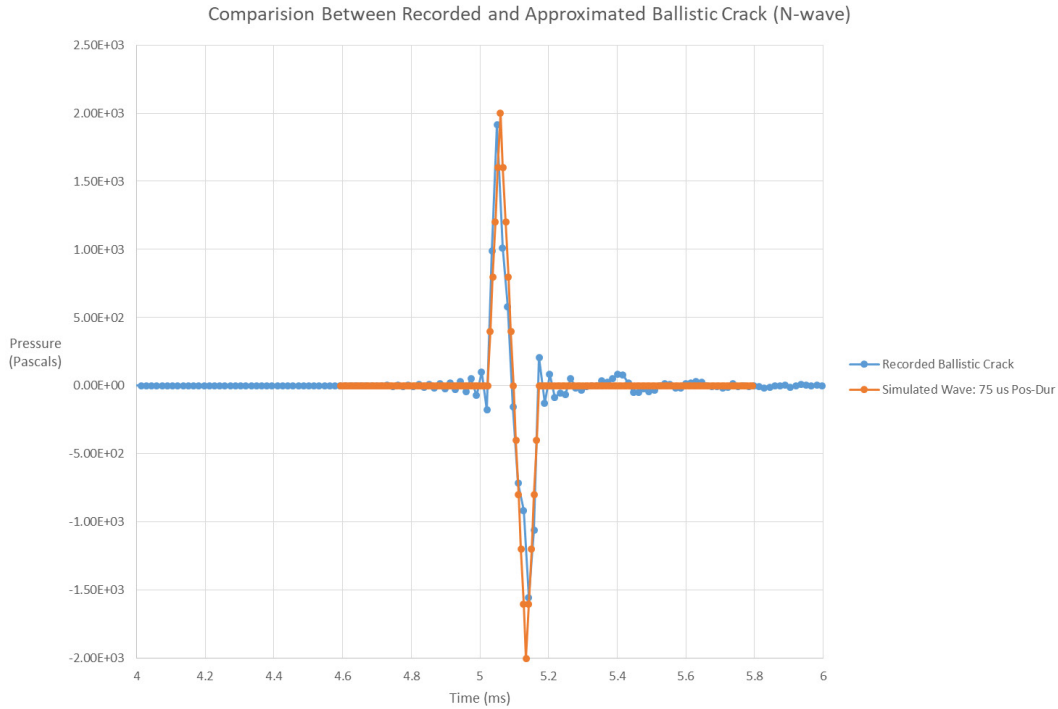
on upward displacements of the basilar membrane, AHAAH can easily predict less hazard from a waveform with greater AwE. Upward basilar membrane displacements are produced when the stapes moves outward from the cochlea. A lower-energy waveform that repeatedly pulls the stapes from a clipped positive displacement, across the region of large compliance about zero displacement, to a clipped negative displacement, can produce a large upward displacement of the basilar membrane. AHAAH predicts that such an action will result in more damage than the amount of damage caused by a waveform having much higher energy that simply pushes the stapes to a clipped positive displacement and allows it to slowly relax back to zero.

By the dynamics represented in the AHAAH model, waveforms with rapid transitions from positive pressures to negative pressures can produce more damage than waveforms with greater energies but less frequent, and less rapid, positive-to-negative-pressure zero-crossings.

To clearly illustrate how AHAAH hazard predictions change with waveform characteristics and distinguish differences between AwE hazard predictions and AHAAH ARU hazard predictions, it is essential to clearly distinguish between hazard changes caused by differences in waveform amplitude and hazard changes caused by differences in waveform time-dependence.

To illustrate differences associated only with changes in waveform time-dependence, we have applied a waveform approximating the ballistic crack caused by the passage of a supersonic projectile, such as a bullet. Ballistic cracks are described in detail by Haering et al. (2006) and shown by Dater (2014).

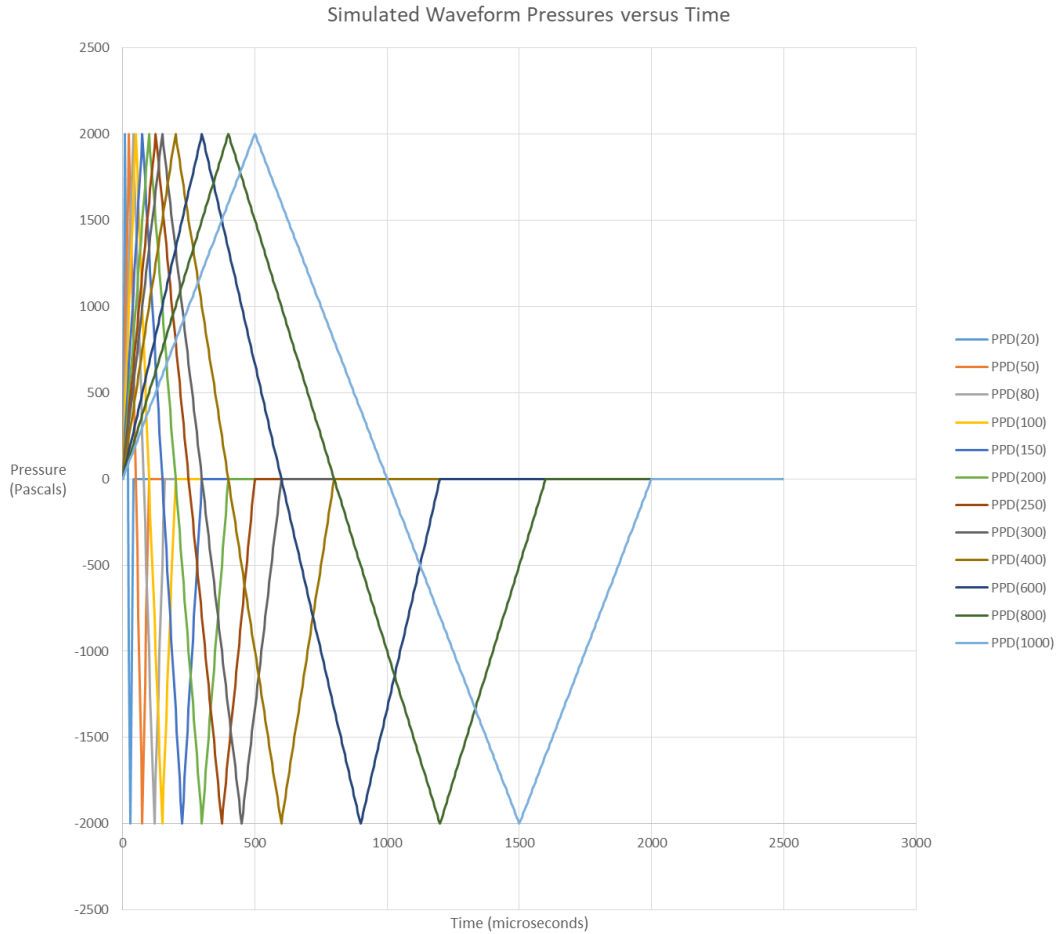
Our illustration uses simulated waveforms, rather than measured waveforms, because measured waveforms often contain both amplitude and time-dependence variations that obscure the dependence of the hazard on either variation. Figure 2 shows a comparison between a measured ballistic crack and the form of simulated waveform we have applied.



**Fig. 2 A recorded ballistic crack and a simulated waveform with a PPD of 75  $\mu$ s**

Although the simulated waveforms are not real, comparison between a recorded ballistic crack and a simulated waveform shows the simulated waveforms closely approximate actual ballistic cracks when an appropriate PPD is applied. The simulated waveform in Fig. 2 has a PPD of 75  $\mu$ s. The recorded ballistic crack shows artifacts of the recording process. In the simulated waveform, we approximated the positive and negative pressure durations of the ballistic crack by applying symmetric positive and negative pressure amplitudes, and a linear pressure change with time, to create a single wavelength of a saw-tooth waveform, with a time-averaged pressure equal to zero.

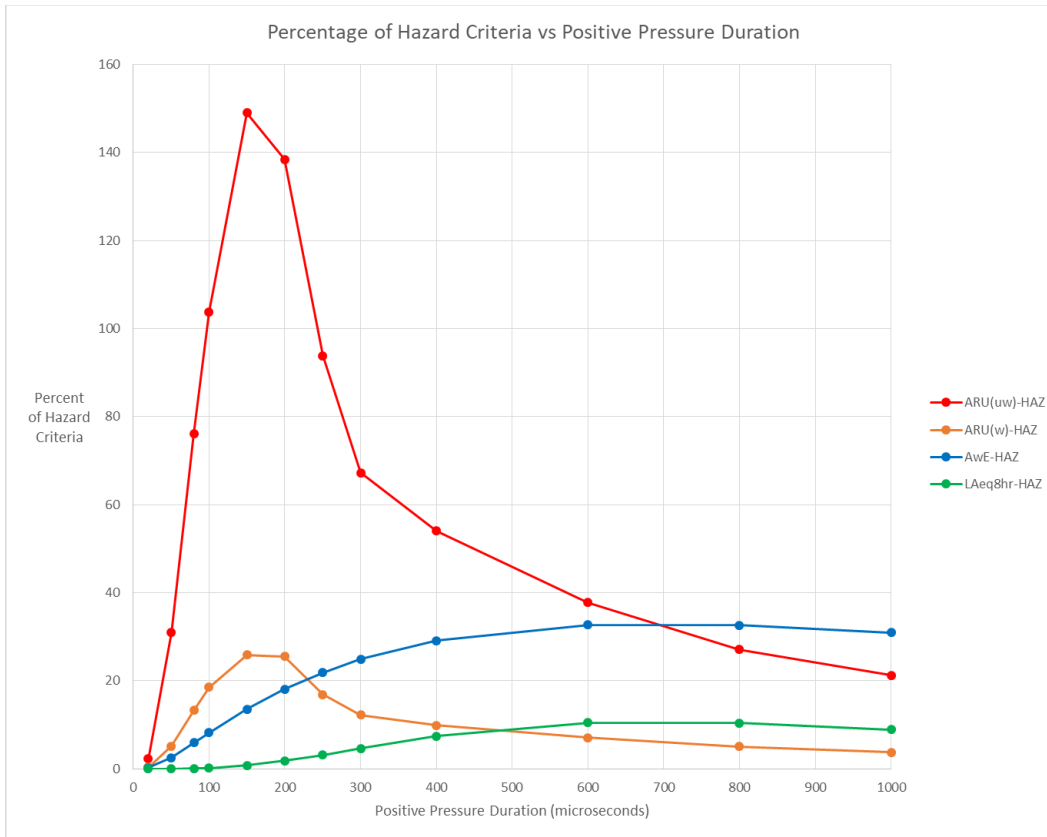
Starting with a minimum PPD of 20  $\mu$ s, we created a series of saw-tooth waveforms with additional PPDs of 50, 80, 100, 150, 200, 250, 300, 400, 600, 800, and 1000  $\mu$ s. These waveforms are illustrated in Fig. 3 and are also included as attachments to this technical note.



**Fig. 3 Overlaid waveforms with various PPDs shown in microseconds in legend. (The waveforms are included as attachments to this technical note.)**

The original waveform has a PPD of 20  $\mu\text{s}$ , obtained by using a rise time of 10  $\mu\text{s}$ , as shown in Fig. 3. Each of the generated waveforms has an AwE easily calculated using Fourier analysis and provided by AHA AH output.

Using these waveforms, we calculated the percentage of the maximum allowed exposure criterion for the AHA AH Unwarned criterion, the AHA AH Warned criterion, the AwE constant energy criterion, and the LAeq8hr allowed dose criterion. The percentage of each criterion's allowed exposure level is plotted in Fig. 4 as a function of the PPD of the waveform.



**Fig. 4** Percent of allowable hazard for each hazard criterion: AwE-HAZ, AWE hazard percent; ARU(w)-HAZ, ARUs (Warned) hazard percent, ARU(uw)-HAZ, ARUs (Unwarned) hazard percent; and LAeq8hr-HAZ, LAeq8hr hazard percent

MIL-STD 1474E, paragraph B.5.3.4, notes, “Energy-based hazard assessments overestimate hazard for waveforms with positive pressure durations greater than 200 μs” (AMRDEC 2015). This behavior has not been corrected in these calculations and the AwE constant energy criterion predicts greater hazard than the AHAAH Warned criterion for PPDs above approximately 235 μs. The LAeq8hr criterion predicts more hazard than the AHAAH Warned criterion for PPDs greater than approximately 475 μs. The AwE constant energy criterion predicts greater hazard than the AHAAH Unwarned criterion for PPDs above about 700 μs.

Both AHAAH Unwarned and Warned criteria predict more hazard than either the AwE constant energy criterion or the LAeq8hr criterion as PPDs become smaller than 200 μs. The dynamic processes applied in the AHAAH model for humans were investigated in cat ears and reported by Price and Wansack (1989). Although not all questions about the applicability of the AHAAH model have been answered to the satisfaction of the overall scientific auditory hazard community, Fig. 4 shows that AHAAH is not necessarily under-predictive of auditory hazards and greater

hazard may exist from waveforms that are considered less hazardous by energy considerations.

## 4. Conclusions

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Figure 4 shows that hazard predictions for the two hazard assessment methods in MIL-STD-1474E (AMRDEC 2015) differ most significantly for waveforms with PPDs between 100 and 200  $\mu\text{s}$  and nearly equal maximum positive and negative pressure amplitudes. Measurements, or further validated finite-element modeling of auditory damage produced by such waveforms, will have the most significant impact in establishing the validity of either MIL-STD assessment method.

Establishing the validity of either of the hazard assessments shown in Fig. 4 is important. Impulsive waveform recordings often show a small number of major pressure peaks; it remains important to accurately assess the hazard presented by these major impulse features. However, recorded waveforms also often show a large number of high-frequency pressure fluctuations. Underestimating the hazards of these many fluctuations could easily result in a significant underestimate of a waveform's hazard, especially if no association is made between the time-dependence of the hazard evolution and the time-dependence of the waveform. While hazard assessment measurements with humans should never be performed because of the hazards of recognized hearing loss, as well as the hazards of hidden hearing loss (Plack et al. 2014; Liberman 2015), research results obtained with cadavers, scaled mechanical systems, or finite-element models may provide the techniques needed to resolve appropriate damage behaviors and help to resolve the existing uncertainty between various hazard criteria.

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## List of Symbols, Abbreviations, and Acronyms

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AHAAH	Auditory Assessment Algorithm for Humans
AMRDEC	Army Aviation and Missile Research Development and Engineering Center
ARL	US Army Research Laboratory
ARU	auditory risk unit
AwE	A-weighted energy
MIL-STD	Military Standard
PPD	positive pressure duration

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