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The Auditory Hazard Assessment Algorithm for Humans (AHAAH): Hazard Evaluation of Intense Sounds

by G. Richard Price

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14. ABSTRACT

Prediction of hazard from intense sounds requires that predictive algorithms match the properties of the ear. The existing damage risk criteria do not and, as a result, perform badly. At the very high levels typical of gunfire, the ear has distinctive properties. The primary loss mechanism is mechanical stress within the cochlea. The conductive path exhibits spectral tuning, middle ear muscle attenuation of transmission, and peak limiting of stapes displacements. To deal with these issues, the AHAAH model was developed as a first-principles electroacoustic analog of the ear that matched these properties. It has been peer reviewed and shown to predict hazard to the human ear much more accurately than any other approach. It accommodates HPDs in the analysis, and its theoretical basis assures its generalizability to new impulses. It also has features which allow insight into engineering solutions to problems and promotes better HPD design and use. The model has been used internationally by the armaments community and the SAE, and it is being proposed as an ANSI standard for intense noise exposure. It is available for immediate use as a health hazard assessment tool and a design tool for the military.

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1. Introduction

We will attempt to provide a unifying conceptual context for hazard evaluation and model development that will be helpful in dealing with the complexities in this area. This discussion will not cover the detailed development and validation of the auditory hazard assessment algorithm for the human ear (AHAAH) model which has been published, appeared on websites, and will be referenced. We will focus on the science and philosophy underlying critical elements of the ear's physiology that must be accommodated for accurate predictions. We will also cover the basis for the model's design and the implications for its use, comparing and contrasting it with alternate procedures. Finally, we will address its validation and the issues associated with the available data sets used in evaluating a damage risk criterion (DRC) for intense sounds.

1.1 Historical Context

For the American military, the problem of predicting and ameliorating the effect of very intense sounds on hearing can be traced to our experience in World War II. Given the primitive state of acoustic instrumentation in those years, the inherent difficulty of working at very high sound pressure levels (SPLs), the very limited knowledge of the ear's behavior at high intensities, as well as a lack of official interest that produced little funding, research in the early years was understandably sporadic and largely descriptive. Nevertheless, by the 1960s and 1970s, several attempts had been made to relate some parameters of the measured sound to potential hazard for the human ear. The United States and United Kingdom had an approach based on the work of Coles et al. (1967, 1968), which was the basis for MIL-STD-1474D (1997); The Netherlands had the Smoorenburg criterion (Smoorenburg, 1982); and Germany had the Pfander criterion (Pfander, 1975). They all had been developed primarily with small arms exposures, depended on measures of peak pressure and duration, and were essentially linear. None of these standards specifically accounted for the acoustic or physiological characteristics of the ear but focused on finding a measure of the sound that could be reliably made and empirically related to hearing loss by correlational techniques. The ear was treated as a black box, and higher sound pressures and longer durations were associated with greater hazard.

In the same vein, A-weighted energy has been proposed as a measure that could be correlated with hazard. Insofar as the A-weighting function is derived from measurements of the loudness of a sound, it does open the black box of the ear and reflects some of the characteristics of the conductive path. It is now widely used in evaluating noise hazard from common industrial sources (sound pressures from 80 or 85 dB up to 110–115 dB) and is being considered as a measure up to the very highest levels (185+ dBP). In any event, we shall see that all these approaches lack the theoretical base needed to address the true complexity of the ear's response to intense sounds at the level of gunfire (155–185 dBP).

1.2 Design Philosophy of AHAAH

In contrast to the previous approaches, the AHAAH was developed from a theoretical perspective. The decision to work using a first-principles approach was made deliberately, recognizing that it involved great technical complexity and that such an approach had not been used before in developing a DRC. At the same time, the decision was also made to make the model an electroacoustic analog of the ear conformal with the structure of the ear. Lumping parameters would have produced a simpler structure and fewer variables. However, maintaining parallelism between the model's elements and the ear's physiology promotes flexibility and insight. Such an approach enhances generalizability and enables insights into mechanisms that could be exploited to reduce auditory risk as well as promote the design of weapons systems that are both more effective and inherently less hazardous.

1.2.1 Generalizability

As previously noted, most standards have been developed with correlational techniques in which ears were exposed to some given type of impulse and the effect on hearing threshold measured. In such a case, one can use the results confidently (given that within- and between-subject variables are not a problem) as long as any new test impulses are exactly like those used in the original tests. MIL-STD-1474D, for example, is problematic in that it was based almost entirely on unprotected exposures to small arms fire; yet it has been used to predict protected exposures to cannon fire as well. The problem is that, in practice, new impulses are often very unlike those used in the standardization studies and considerable extrapolation is necessary. This is particularly dangerous when it is not clear that there is a meaningful continuum along which impulses are being ranked. For example, the existing standards use peak pressure, duration, or energy, which, at first blush, would appear to relate to hazard. However, there are other variables internal to the ear that are critical in the production of hazard. As a result, the traditional variables tend to fail badly, i.e., they greatly overpredict the hazard from large-caliber weapons. If, on the other hand, the criterion is theoretically based, the relationship between the measurements and the variables producing hearing loss are more closely related, predictive ability increases, and the risks associated with extrapolation are very much smaller.

1.2.2 Insight

In addition to generalizability, the theoretical approach offers the potential for meaningful design insight, enabling the creation of less hazardous products, as well as the potential for improved system performance. For example, if we measure the weighted energy in an impulse, then we have lost the information in the waveform regarding the details of exactly when the energy was delivered in the impulse. This loss is critical to assessing hazard. Calculations with the AHAAH model have shown that the exact timing of the peaks and dips in the waveform does matter for particular impulses. For example, in the presence of a peak-clipping nonlinearity produced by the stapes suspension, the timing of peaks and dips in the waveform is important in determining the energy that gets transmitted to the cochlea, where it can do damage. Using this feature of the

AHAAH model, it has been demonstrated that exposure to automotive airbag noise is safer with the windows closed, even though the pressures are higher (peak clipping during the higher pressure reduces the flow of energy to the inner ear) (Price, 2006). It has also been shown that an impulse from a rifle with a muzzle brake can be no more hazardous than the impulse from a standard weapon (Price, 2011), despite much higher peak pressures and energies associated with the muzzle brake. If a DRC evaluates only peak pressure, duration, or energy, then the only advice that can be given to the designer is to reduce what was measured—advice, which, if followed, may not have the desired effect. With theoretical insight, however, weapons can be designed that are both safer and more effective.

2. Critical Insights From Basic Research

It is obvious that any successful characterization of the ear's response to intense sound must reflect relevant elements of the ear's structure and how they respond to particular sounds. These are the bedrock—the nonarbitrary elements that must be accommodated by a successful method. Therefore, in developing AHAAH, we began by focusing on the processes that operate within the ear at high intensities. We then moved to creating accurate model(s) of these processes and finally deriving the appropriate acoustic analyses.

2.1 Change of Loss Mechanisms

Basic research on the ear's acoustic properties has produced several key findings, which must be accounted for if any DRC is to succeed at predicting hazard. First, loss processes change character as intensity rises. At lower intensities, they are like metabolic exhaustion—processes that could be recovered from and repeated daily for many years, with loss growing slowly over time. Loss and recovery processes at these levels are a logarithmic function of time (Price, 1968, 1972; Ward et al., 1959). However, at the very highest intensities, loss processes become essentially mechanical in character. They grow as a linear function of time (Price, 1968, 1972; Ward, 1962) and recovery is delayed and may not go to completion (Hamernik et al., 1988; Luz and Hodge, 1971). Given this change in modes, it is reasonable to suppose that two different analyses may be required—one for high levels and another for lower levels. At any rate, it is at least imprudent (even if convenient) to expect that one approach will work across the entire range of intensities from 85 to 185 dB.

The earliest and major physiological effect at very high intensities is at the level of the outer hair cells within the cochlea, probably acting on the tip links first. At these levels, the insult can be analogized as akin to a fracture or a sprain in the musculoskeletal system; the onset of loss is very rapid and the recovery prolonged. Fortunately for our proposed analysis, this has made the modeling somewhat simpler in that the rapid recovery processes appropriate to metabolic loss mechanisms did not have to be included in our algorithms. Also, the changes in hearing level measured one-half hour or so after the insult are relatively stable (Hamernik et al., 1988). In contrast, the changes in hearing level after lower level exposures are complex and change rapidly (Hirsch and Ward, 1952).

The change in loss mechanisms does mean that it may not be scientifically justifiable to combine hazard calculations from high- and low-level stimuli and treat them as equivalent. A criterion threshold shift from very intense impulses should not be considered as equivalent to the same threshold shift produced by lower-level stimuli, where the recovery processes can move to completion rapidly and repeatedly. It does seem likely that there is some level above which exposures can be combined and below which they can also be lumped.

This situation raises a particular concern regarding proposed uses of A-weighted energy as a measure. One of the advantages advanced for an energy measure as a criterion is that combining exposures can easily be done without regard to the level of the exposure. While it may be technically possible to do such a calculation, the procedure is unlikely to properly represent processes active in the ear. In using A-weighted energy as a method, the French have limited its use to peak pressure levels (PPLs) less than 160 dB (Dancer, 2003). In practice, however, pressures much higher than that need to be evaluated (even when measured under an earmuff).

2.2 Spectral Tuning

Secondly, basic research has shown that the conductive path to the inner ear makes a major contribution to the sound arriving at the cochlea and introduces a number of critical nonlinearities into the system. Such considerations are important in establishing an accurate model of the ear. The outer and middle ears act like a band-pass filter, transmitting sound best in the mid-range, while cutting off at low frequencies because of stiffness (at about 12 dB/octave) and at high frequencies because of mass (at 18 dB/octave). These elements are largely responsible for the U-shape of the human audiogram. Alternatively, the spectrum of the sound matters. Given a rifle impulse and an impulse from a cannon with the same peak pressure (spectral peaks differ by more than 3 octaves), the rifle impulse is much more hazardous, even though measures of energy and duration (used by the traditional hazard assessment procedures) are much greater for the cannon. In essence, the rifle impulse has its energy closer to the mid-range, where the ear conducts energy well and the cannon impulse has its energy in the low-frequency region, where the ear doesn’t conduct energy as well. Accurate representation of the energy actually arriving at the cochlea required that the AHAAH model accurately reproduce the conductive path from the free field to the stapes. In contrast, the measures of hazard using measures of pressure and duration (MIL-STD-1474D, 1997; Smoorenburg, 1982; Pfander, 1975) do not consider the spectral distribution of energy.

2.3 Displacement Limiting

Further, basic research indicates that the middle ear becomes a peak clipper at very high intensities. While it is remarkably linear over a wide dynamic range (up to approximately

130 dBP), there are limits as to how much the middle ear structures can move, a critical issue for hazard assessment (Price, 1974). The annular ligament of the stapes limits its displacement to a few tens of microns and produces a strong peak-clipping effect on very intense waveforms. This effect explains why measures not considering this non-linearity may correlate with hearing loss at a lower level typical of small arms yet fail at the higher levels associated with large-caliber weapons. Just because the impulse in air becomes more or less energetic by 10 or 20 dB there is no assurance that the energy in the cochlear input will change by an equal amount. This explains why an L_{AEQ8} of 85 dB will arguably be suitable for rifle exposure but an L_{AEQ8} of 110 dB will be suitable for large-caliber weapons impulses, a disparity of 25 dB (Murphy et al., 2009; Price, 2007). Therefore, in order to reproduce this very important aspect of the ear's physiology, the AHAAH model specifically includes a stapes suspension that hardens as a function of displacement.

This same element confounds the existing criteria in that they establish a "level/number-trading ratio" as part of their formulation. This ratio forms the basis for adjusting the number of rounds allowable by changing the acceptable peak pressure or vice versa. Given the reality of the clipping function, it is obvious that there can be no valid single level/number-trading ratio at high levels. A change in peak pressure level produces different effects on the cochlear input, depending on just how much clipping has occurred (Price, 2005), and the level/number-trading ratio must change with it.

No standard other than AHAAH includes such a refinement of a progressive, amplitude-limiting conductive path. It logically follows that if other standards properly predict impulses at one level, they must necessarily fail at other levels. One might artificially mimic amplitude limiting by prescribing different criterion levels for different impulses—one level for rifles, another for cannons, etc. Such a procedure is obviously flawed because the rules for changing from one level to another are arbitrary. Furthermore, there are individual impulses encountered in practice, which effectively incorporate elements at more than one level.

In the past, when it appeared that large-caliber weapons impulses were less hazardous than anticipated, it was assumed that the hearing protectors worn during the exposures must have worked much better than anyone had previously thought they could (Johnson and Patterson, 1993; Smoorenburg, 1982). In retrospect, it now seems likely that the stapes displacement nonlinearity was responsible for the smaller-than-anticipated losses seen during those exposures. Under other circumstances, it could be disastrous to depend on the apparently "better attenuation" of the hearing protection devices (HPD). Clearly, a more sophisticated analytical tool is needed.

2.4 Middle Ear Muscle Effects

Lastly, basic research has shown that the middle ear muscle system produces time-varying attenuation of middle ear displacement capable of reducing energy transmission by 20 or more decibels at low frequencies (below 1000 Hz) and progressively less at higher frequencies. It would be much simpler if we did not account for middle ear muscle effects, yet they are part of the normal mammalian ear and produce significant attenuations that should be accounted for.

None of the existing criteria, other than AHAAH, make specific allowances for middle ear muscle activity. For industrial noise exposures, which are largely continuous, a simple reduction in sensitivity (increase in allowable level) may successfully accommodate middle ear muscle effects. However, for weapons noise exposure where a single impulse may include as much energy as many months of exposure to industrial noises, the state of the middle ear muscles will materially affect the cochlea's exposure. The AHAAH model is capable of making such a correction.

We conclude that basic research has shown that even if it is possible to measure the pressure history of an impulse in air, the waveform arriving at the stapes (the cochlear input) can be very different. It is this waveform, which has passed through multiple nonlinear processes, that produces insult within the inner ear. The AHAAH model was therefore developed to deal specifically with these insights to produce a more effective hazard assessment.

3. Development of the Model

At the onset of our efforts, the transfer functions from the free field to the stapes were reasonably well known at lower SPLs. This gave us the correct expectation that we could accurately reproduce the conductive path to the cochlea for both cat and man, the models with which we were working. Hence, the challenge for a model that worked at high SPLs was to incorporate the nonlinear elements of the stapes suspension and the middle ear muscle response into the conductive path and develop an algorithm that reflected susceptibility within the cochlea.

3.1 The Conductive Path

The stapes nonlinearity was modeled as a hardening spring, which ultimately limited displacement of the stapes. The middle ear muscle response was modeled as a time-varying stiffening of the stapes suspension produced by the contraction of the stapedius muscle, which rocks the stapes sideways in the oval window. The rate of contraction onset had been studied by Dallos (1964) and the magnitude by many others; therefore, we were able to incorporate a time constant and magnitude of response typical of a normal ear.

3.2 Cochlear Susceptibility

The question of how to evaluate intracochlear factors was problematic. In principle, one could begin with the anatomic details of the organ of Corti, make estimates of their physical properties, susceptibility to fatigue, etc., and build a damage model from the bottom up. However, the living organ of Corti is inaccessible, its structure is mechanically complex, critical data were essentially unknown, and the risks of making estimates were huge.

We therefore adopted an alternate approach to characterizing loss mechanisms within the cochlea. Auditory theory had progressed to where basilar membrane displacements could be calculated, given a waveform at the stapes. Therefore, we decided to address cochlear susceptibility empirically. Given the common structure of mammalian cochleas and the considerable knowledge that had been developed regarding the cat ear in particular, we exposed anesthetized cats to a variety of intense impulses. Anesthetization had the effect of eliminating both movement of the ear during exposure and the confounding effect of middle ear muscle contractions. The model began with free-field pressures, carried them to stapes displacements (to include the peak clipping nonlinearity), and predicted displacement histories at one-third octave intervals along the basilar membrane. Under these conditions, the correlation between the calculated displacements and mean hearing loss of the 12 groups of animals tested, measured immediately after exposure, was 0.94, which left little variance to explain (Price, 2003, 2006). These same data also provided the formula connecting the number of auditory risk units (ARUs) to the number of decibels of compound threshold shift (CTS) measured immediately after exposure (called compound threshold shift because it contained both temporary and permanent components):

$$\mathrm{CTS} = 26.6 \times (\mathrm{LN}\ (\mathrm{ARU})) - 140.1, \tag{1}$$

where ARU = Σ (peak upward basilar membrane displacements in microns, squared) at each of 23 locations on the basilar membrane, upward displacements put tip-links of hair cells in tension, and tissue fails first in tension.

This relationship can be thought of as characteristic of mammalian cochleas. We believe that this clear result was, in part, a function of the fact that the conductive path of the cat was well known and the middle ear muscle system was inactive. Under these conditions, we were observing an essentially pure cochlear phenomenon.

The model for the cat ear was then transmogrified to a human ear by changing the values of the variables within the equations so that they represented the physiology of the human ear. In most human uses, of course, the ears are not anesthetized and the middle ear muscle system is active. We allowed two conditions—one in which the middle ear muscle response is elicited by the sound (called in the model an “unwarned” exposure) and one in which the middle ear muscle response is preexisting. A preexisting response would be expected where the impulse was one of a series, as in machine gun fire, or in the situation in which the person being exposed could anticipate that the impulse was about to arrive (called a “warned” exposure).

3.3 Additional Features

In adopting a theoretically based approach, it became possible to provide additional useful features not commonly found in a DRC. In one instance, the features make it possible to include HPDs directly in the hazard calculation. Because it is conformal with the structure of the human ear, the AHAAH model can allow input of waveforms measured in the free field, at the ear canal entrance, or at the eardrum position. In each case, the appropriate transfer functions are calculated. It is thus possible to use waveforms measured under HPDs and include their effect in the hazard calculation. Of course, measurement at the eardrum position presumes the use of an acoustic manikin, which brings with it a host of other technical concerns; however, it does provide a waveform for analysis. Alternatively, it is possible to calculate the effect of an HPD on the input waveform (Kalb, 2010a, 2010b). There are, in fact, many sources of variance associated with HPD use, poor fit being a prime example. Whatever choice is made with respect to how HPDs should be included, the AHAAH model is capable of incorporating a wide range of approaches.

An A-weighted energy criterion is also capable of using measurements made on an acoustic manikin and processing the calculated waveform. However, there is potentially a large error inherent in such a use. The shape of the A-weighting filter presumes free-field stimulation, which includes the transfer function(s) from the free-field to the eardrum. If pressures are measured at the ear canal entrance, then the effect of the transfer function from the free-field to that location should be subtracted and likewise for pressures measured at the eardrum.

The other criteria use single number adjustments to account for HPD effect, an approach that simply ignores the large and increasingly complex effects of HPDs. Nonlinear HPDs, such as the combat arms earplug, are increasingly being used by troops because they provide protection and allow situational awareness. Obviously, single number adjustments for HPDs do not effectively represent these devices. The AHAAH model simply needs a waveform to do its calculation; therefore, recordings acquired on an acoustic manikin or calculations done with a mathematical model of the protector could provide such a waveform.

A second type of novel feature included with the AHAAH model is a movie that shows the calculated action of the waveform within the cochlea. For low-level exposures to continuous sounds, such a display is not particularly useful. During long exposure, many things vary—middle ear muscle state, angles of incidence, HPD fit, etc. For exposure to very intense impulses, the details of the action can be critical. An immense amount of energy is received in milliseconds. For such cases, details, such as angle of incidence and temporal patterns in the energy, are important. The movie can show exactly what part of the waveform had the greatest influence on hazard and what didn’t matter. Such information can provide engineering insight into ameliorating or eliminating the hazard. For example, in the case of airbag noise exposure in a closed passenger compartment, the movie revealed that the high peak pressures were not transmitted to the cochlea because of the peak-clipping effect of the stapes. Partly because of this feature, the SAE uses AHAAH to assess acoustic hazard from airbags (SAE Standards, 2003). And technology transfer is occurring: some more sophisticated modern cars close windows in the event that a collision is sensed in order to preserve hearing. In another case, the movie showed that the physical “bounce” of the airbag was material in increasing the exposure by about 75% and conversely, that restraining the bounce would reduce the hazard accordingly (Price, 2006).

3.4 Creation of User-Friendly Software

If an analysis program is to succeed at having a constructive effect outside the laboratory, it must be possible for people other than the designers to use it. The AHAAH model has been structured to run on a PC-level computer, in essentially real time, employing user-friendly software requiring a minimum of specialized training (Binseel et al., 2009). Over the last 10 years, the AHAAH model has been successfully translated into other programming languages (C, Matlab) and has been used by the U.S. Army and the Israeli Defense Forces in making health hazard assessments, by the Society of Automotive Engineers in analyzing airbag noise, and by other laboratories as a research tool.

4. Validation and Acceptance of the AHAAH Model

4.1 Considerations Regarding Data Sets Used in Validations

One of the difficulties in working in this area is that it is very difficult to obtain data from human subjects. The stimuli are potentially damaging; therefore, human use considerations constrain experiments. In addition, the problems associated with exposure to live fire or simulation of weapon noise through the use of explosives are daunting. In the past, our understanding of the risk was poorer and the constraints were fewer, e.g., subjects could be tested with live fire and without hearing protection. The result is that today we have a mix of experimental data, collected under different conditions, with very different experimental designs. An understandable response on the purist's part would be to throw up one's hands and propose starting all over again; but practical considerations suggest that this is not likely to happen, nor is it necessary. For the foreseeable future, the best strategy will be to make use of all the data we have. These data are much more comprehensive than those we have had in the past, and, given a theoretical perspective (rather than depending on correlations), they can serve as an adequate basis for a DRC. Additional data, especially in the 135–155 dBP region, would be desirable; but we need not await their arrival. In the event that new data are developed requiring revision of an existing standard, this process exists, and an improved version can be quickly produced and adopted.

4.2 Problems With the Albuquerque Studies (AS)

The U.S. Army's AS, in which 53 different conditions were tested with large numbers of subjects (S), are clearly the most extensive studies available. Yet there is enduring controversy regarding their analysis and interpretation. Some have recently conducted extensive, sophisticated, statistical analyses of these results (Murphy et al., 2009). However, even sophisticated statistical analyses depend on an accurate correspondence between the statistics and the physical basis of the data being analyzed or the numeric results have no meaning (Price, 2010a, 2010b). Despite all of their strengths, these studies have proven to be something of a conceptual nightmare. They used a repeated-exposure design in which the S showing a 15 dB or greater threshold shift was dropped in the next test condition to a less energetic exposure. The expectation was that if they received exposure at a higher level, those ears would surely fail, perhaps producing permanent threshold shifts. A recent analysis of the data in the AS showed that of the 28 S's experiencing a 15–25 dB threshold shift, 25 went safely on in the exposure matrix to higher levels, sometimes much higher counter to the expectation (Price, 2010a, 2010b). Clearly, assumptions regarding susceptibility need to be reexamined. The same analysis also provided evidence that, in spite of rigid experimental controls, some exposures for individual ears were five to seven standard deviations above the average for the group. Because there is no full report of exposures to individual exposures for all the ears, it is impossible to know for sure whether or not the threshold shifts seen were, in fact, the result of the "rare event" higher exposure or a loss experienced by a more susceptible ear.

4.3 Constructive Use of the Data

Despite all the reservations with respect to interpreting the data, at least two observations seem to be solid. First, unprotected exposure to about five or six impulses from a military rifle is capable of producing unacceptable risk in a susceptible firer. In terms of A-weighted energy in air, that is an exposure to approximately an 85 dB_{LAEQ8}. In contrast, the ear is much less sensitive to exposure to large-caliber weapons impulses—intense impulses with energy in the lower spectral frequency regions. The data from the AS indicate that a 110 dB_{LAEQ8} would be acceptable (exposure measured under an earmuff). These findings are in keeping with the arguments earlier in this report that an analysis method not accounting for the stapes nonlinearity must overestimate the hazard of large-caliber impulses if it is correct for small arms. A single valued, A-weighted criterion, such as 85 $dB_{LAEQ8,}$ does not work; and as theory argues, it simply <u>cannot</u> work.

On the other hand, the AHAAH model captures the essence of the situation, correctly assessing the hazard for both small arms and large-caliber weapons impulses, all without adjustment.

4.4 Technical Validation

In 2001, the AHAAH model was peer reviewed by the American Institute of Biological Sciences at the request of the U.S. Army Medical Research and Development Command. In the end, the panel assented to the following statement articulated by LTC Karl E. Friedl as part of the review analysis:

> The Panel recommends that free-field pressure traces should be input to the model, using the "minimum-phase" model of hearing protection and "unwarned" ears, and that personnel be allowed to be exposed to combinations of noise that does not result in more than 500 ADUs per day. The Panel feels that it was satisfactorily demonstrated that this limitation would produce 95/95 protection – that is, there is 95% confidence that 95%

> of the population will experience temporary threshold shift (TTS) that is less than 25 dB. The Panel feels that the process can be applied to all impulse noise conditions, including those whose pressure-time histories appear to be quite different from the ones collected in the Albuquerque study, and still provide the same protection. Finally, the Panel feels that this criterion will provide adequate protection against unacceptable auditory damage over the soldier's occupational lifetime, as long as the devices are worn and properly fit.

The ultimate test of a theory is whether or not it predicts outcomes. Given a waveform recorded in the free field, at the entrance to the ear canal, or at the eardrum, the model is designed to predict threshold shift measured immediately after exposure for the 95 percentile ear (other percentiles are calculable). Threshold shifts of 25 dB or less appear to be recoverable and have been taken to be the limit of safe exposure.

Price (2007) published a validation for the AHAAH model, which addressed all the available human data and compared MIL-STD-1474D and A-weighted energy on the same data. The findings in that study support the contention that a theoretical approach should predict much better and the outcomes for the other two criteria are consistent with the arguments developed in this report. Namely, the standards that do not adjust for stapes nonlinearity tend to overpredict the hazard from large-caliber, low-frequency impulses while predicting small arms exposures reasonably well. Using simple statistical concepts consistent with the wide range of data sources and types, it was argued that the AHAAH model predicted the correct outcome in more than 95% of over 70 experiments. The other criteria were much less accurate (42% accuracy for MIL-STD-1474D [protected exposures only] and 25% for A-weighted energy). The errors for MIL-STD-1474D and A-weighted energy were, in some cases, very large (in the direction of overprediction of hazard).

In the pursuit of good science, we have sought additional human noise-exposure data. However, as of this writing, we know of no noise exposure data from human ears that challenge the accuracy of the AHAAH model.

4.5 Peer Recognition

- In addition to technical accuracy, peer recognition is one of the hallmarks of superior science. Bodies outside the U.S. Army Research Laboratory have repeatedly recognized the technical contributions made by the model.
- The Society of Automotive Engineers has adopted the AHAAH model as the calculational basis for the Recommended Practices Document SAE J2531 used internationally for assessing hazard from airbag impulses.

- In 2007, The National Hearing Conservation Association awarded Dr. Price their "Outstanding Hearing Conservationist Award" for the work associated with the AHAAH model.
- In 2008, the AHAAH model was featured in an invited plenary address to NOISECON08, Dearborn, MI.
- At present, ANSI WG-S3-62 "Method for Rating Hazard to Hearing from Very Intense Sounds" is preparing a draft standard, which includes the AHAAH model as a method for analyzing sounds.

5. Summary and Conclusions

Successful prediction of hazard from intense sounds requires that the predictive algorithms match the properties of the ear. The existing DRCs do not do this and, not surprisingly, have been shown to perform badly when challenged with a broad range of impulses.

Basic research has established that the ear has distinctive properties when it operates at the very high levels typical of gunfire. The primary loss mechanisms are intracochlear and are based on mechanical stress within the organ of Corti. At those levels, the conductive path exhibits spectral tuning, middle ear muscle attenuation of transmission, and peak limiting of stapes displacements.

The AHAAH model was developed as a first-principle, electroacoustic analog of the ear that included the basic research insights into the ear's function at high levels. It has been peer reviewed and has been shown to predict the onset of hazard in the human ear much more accurately than any other approach. Additionally, it accommodates HPDs in the analysis, and its theoretical basis assures generalizability to new impulses that may vary from those upon which it was initially tested. It also has features which allow engineering insight into the loss process that will, in turn, promote safer, more effective designs, improved HPDs, and use strategies.

The model has been used internationally for over 10 years within the armaments community, has been incorporated by the SAE in their recommended procedures for airbag design, and is being proposed as an ANSI standard for intense noise exposure.

The AHAAH model has been tested and is ready and available for immediate use as a health hazard assessment tool and a design tool for the military.

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