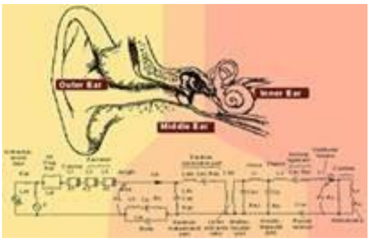
Weapon Noise Exposure of the Human Ear Analyzed with the AHAAH Model



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Predicting the hazard from intense impulses, such as weapons fire or airbags, has remained an intractable problem. The U.S. Army has developed a theoretically based mathematical model of the ear designed to predict such hazards. To establish its validity as a predictor of hazard for the human ear, data from the literature (a waveform and changes in hearing sensitivity) were processed with the model and its ability to predict the onset of unacceptable threshold shift (25 dB or more) in the 95 percentile ear was determined. For comparison, MIL STD-1747(D) and A-weighted energy were also used to compute hazard for the same data. The primary dataset was that of the US Army's "Albuquerque Studies" (53 different cases) and other impulses from the literature (16 additional predictions). The AHAAH model predicted correctly in 95% of the cases, the MIL STD-1474(D) was correct in 38% of the cases and A-weighted energy was correct in 25% of the cases. Errors for all methods tended to be in the direction of over-prediction of hazard. The AHAAH model is not only more accurate but has the advantage of being theoretically based, which improves the likelihood of its being correct on new impulses with novel pressure histories.

I. Introduction

Rating the noise of intense impulse noises has been a perplexing technical problem for many years. The recent consensus of the scientific community has been that none of the existing standards is accurate (Chan, Ho, Kan, Stuhmiller, & Mayorga, 2001; NATO, 2000; 1987). A long-term effort at the ARL has recently produced the auditory hazard assessment algorithm for the human ear (AHAAH) (Kalb & Price, 2002; Price & Kalb 1987, 1991, 1998). AHAAH is essentially a theoretically based electroacoustic analog of the ear designed to predict hazard from any intense sound. The prediction is based on pressure measurements in the free field, at the tragus or at the eardrum, the effects of which are propagated though the middle ear and end in the calculation of basilar membrane displacements. Then, algorithms calculate the "dose" (summed mechanical stresses) at 23 locations within the cochlea. The output is in auditory hazard units that yield a prediction of immediate threshold shift, which in turn also provides a prediction of permanent threshold shift and hair cell loss. A copy of this software and instructions about its operation are now downloadable at the AHAAH website at https://www.arl.army.mil/AHAAH/.

A. Need for accuracy

Ideally, a noise standard should be theoretically based, easy to use, unambiguous in its application and most importantly, for the military, it should predict hazard accurately. The need for accuracy is critical from two perspectives. If the true hazard is under-estimated, hearing loss will be produced in the exposed population. In addition to the great personal loss associated with deafness are the costs of force preservation and loss in mission effectiveness. The other perspective is just as compelling, however. If the true hazard is over-estimated, then weapons designs will be limited, the chances of mission success will suffer and casualties will result because of limited range or power of the weapon system. Neither inaccuracy is acceptable; both types must be avoided. Actually, the argument regarding the need for accuracy can be made for noise hazard assessment in the civilian world as well. A current example would be the problem of airbag design in the automobile industry where underestimation of hazard will result in loss of hearing in those exposed (Yaremchuck, 1998; Fleischer, Muller, Heppelman, & Bache, 2002; Price, 1998a; Saunders, Slattery & Luxford, 1998) and overestimation of hazard could result in ineffective airbag designs that would fail to protect from injury. Here too, the goal of a DRC should be accurate prediction of hazard. The purpose of this paper is to document the accuracy of the AHAAH procedure in predicting threshold shift in human data and to compare it with other methods of analysis.

B. Data analysis

AHAAH operates by processing a digitized waveform. High resolution digital recordings provide the best analysis. Failing that, pictures of waveforms can be digitized but there is a great loss in dynamic range as you go from the visual to the digitized auditory world. A good visual display can provide only about 30 dB of dynamic range, enough where peak pressures are being measured; but not good enough where an algorithm employs all the information in the waveform. In the pressure regime around weapons, it is relevant to note that a reduction of 30 dB from 185 dB is still 155 dB! Therefore, formal analysis with AHAAH had to be restricted to those waveforms for which digitized recordings were available. Of course, in order to confirm the prediction of hazard, it was also necessary that human threshold shift data also had to be available for exposures to the waveforms.

Today there are about 70 exposures that meet these requirements. Most of these (53) come from the U.S. Army's recent experiments using human volunteers (Johnson, 1998,1994). The remainder come from the impulse noise literature of the 1960s and more recent studies. An additional critical point is that the all the newer data from experiments are from subjects with protected ears, whereas the earlier studies were typically done with subjects wearing no hearing protection.

Even when the digitized waveforms and human threshold shift data are available, comparisons between studies and criteria are complicated by a lack of a common basis in reporting data. Studies may provide unique measures of effect, e.g., number of impulses to reach some criterion (some amount of threshold shift in an ear(s) at some frequency(s), number of subjects reaching a criterion threshold shift, number of subjects not recovering in a given time period, etc. Because of the way they were derived, criteria do not use a common data set or use the same data to predict a satisfactory outcome.

To cut through this Gordian knot of non-common information use, in this report we adopted a viewpoint that provides a common method of comparison. DRCs are now commonly designed to protect the 95 percentile ear (most susceptible). So the problem for comparison of rating methods becomes determining whether any given exposure will produce an unacceptable threshold shift in the 95 percentile ear, now commonly held to be 25 or more decibels at any frequency. At the very high exposure levels around weapons (well in excess of 140 dB peak), the loss mechanism is thought to be mechanical stress - akin to a fracture or a strain in the musculo-skeletal system. It appears that 25 dB of threshold shift is tolerable and would be expected to produce no permanent threshold shift from at least occasional exposure (Johnson, 1998; NATO, 2000, 1987).

In this article, we will consider the Army's recent experiments first, then the individual studies.

II. ANALYSIS OF the Exposure Data

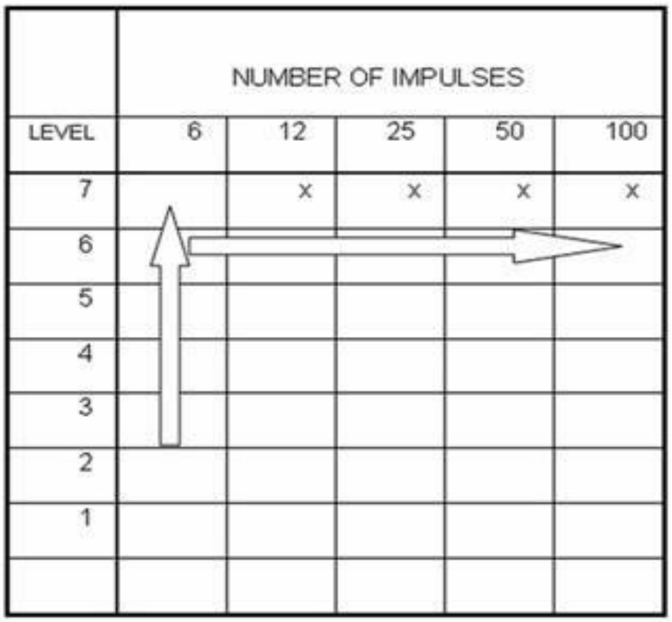
A. The Albuquerque studies

The U.S. Army has conducted the most extensive set of studies of impulse noise exposure of protected ears ever undertaken (Johnson, 1998, 1994; Patterson, Mozo, Gordon, Canales & Johnson, 1997). Given that they were conducted at a facility near Albuquerque, NM, they have become collectively referred to as "the Albuquerque studies". The studies were well and carefully conducted, documented far more completely than previous work and represent the greatest source of data about protected human exposure to intense impulses of which we are aware. In them, the exposure pressures were also far higher than in most studies, higher even than those around modern weapon systems. The highest peak pressures tested were in excess of 195 dB! Given the difficulty and cost in conducting such research with human volunteers, it seems unlikely that this database will be superseded in the foreseeable future.

There were, however, a number of surprises during the conduct of the study that affected the essential design of the experiment and its interpretation. Fortunately, the study was documented well enough that effects of these unusual situations are for the most part known. We will consider first the essential design of the study and then comment on the features that warrant special attention.

1. Design of the studies

The design of this series of studies was based on the concept that exposure to impulses produced by exploding C4 charges of differing weights and physical locations would simulate exposures to generic large caliber weapons used by the Army. The exposure scheme was delineated as diagrammed in Table I. Each level of the exposure was intended to be a 3-dB increase in the peak pressure of the impulse and a doubling of its energy.



	NUMBER OF IMPULSES				
LEVEL	6	12	25	50	100
7		x	x	x	x
6					
5					
4					
3					
2					
1					

Table I. Exposure matrix for the Albuquerque studies

A particular exposure was considered dangerous for a subject if it produced a 25-dB or greater threshold shift at any test frequency. This was referred to as a "full audiometric failure". In practice, however, if a threshold shift of 15 to 24 dB was produced at a particular level, the experimenters were unwilling to expose that ear to the next higher level. In such a case, a "Conditional Failure" was recorded at the next higher level.

Subjects entered the exposure matrix (Table I) at the lower left corner (Level 1, 6 impulses) wearing a circum-aural hearing protective device and if they had no significant threshold shift they progressed to the next higher exposure, Level 2, 6 impulses, and so on up the left side of the matrix as indicated by the "up" arrow. When they reached Level 7, 6 impulses, and passed it, they dropped back to Level 6 and were exposed to increasing numbers of impulses, as indicated by the right-pointing arrow. If they received no significant threshold shift, they were exposed to the next higher number of impulses. If they reached Level 6, 100 impulses, they had successfully completed the course of exposures. If, however during the course of traveling this path, a subject experienced a significant threshold shift, he was dropped down in level and moved toward more impulses at the lower level and so on.

In the initial conception of the study, it was presumed that failures would occur as the levels increased and that the subjects would "migrate" on a "just safe" path through the matrix at lower levels and increasing numbers of impulses. It was also presumed, on the basis of existing DRCs that double hearing protection would be needed in order to complete the matrix but it was not necessary. In fact, the ear appears to be surprisingly robust and such failures occur less often than might be expected. As a result, only a few subjects were tested on the interior cells of the matrix (Levels 1 through 5 and 12, 25, 50, and 100 impulses) and the data there are only suggestive.

2. The exposures

The free field impulses were designed to be Friedlander-like impulses characteristic of Army weapons. The apparatus necessary to produce these impulses took two basically different configurations. The exposure referred to in the reports as the 5-meter conditions had a bare charge suspended about 3 m above a concrete pad, 5 meters from the subjects. For the 3-meter and 1-meter exposures, a mortar-like exposure device was fabricated and the subjects were seated on a circular expanded metal platform with their ears just above the level of its "muzzle," about 3 m above the ground. The subjects were located either 1 or 3 meters (approximately) from the edge of the barrel, thus the designation 3 meter and 1 meter conditions. In acoustic terms, the A-durations of the impulses were about 2.6 msec, 1.5 msec and 1.0 msec respectively. The pressure histories of the impulses and their energies, etc. have been reported in Patterson et al. (1997) and in Figure 3 of Chan et al. (2001).

The reverberant impulses were produced in a steel-walled chamber (3M x 3M x 2.44M) and had much longer durations. They were intended to simulate weapons fired from bunkers, within rooms, or the pressure history within the crew compartments of fighting vehicles. An explosive charge was fired outside the chamber at the end of a barrel that extended into the chamber. The B-durations for these impulses were several hundred milliseconds long. The waveforms for these impulses have been published in Johnson (1998), and an example of the pressure history of the impulse in the room appears in Figure 1. Note that the x-axis in this figure is 500 msec long. The actual peak pressures of these impulses were 184 dB at Level 7 and 182.5 dB for level 6. The impulse that the ear actually saw, however, was that under the muff. An example of that waveform is presented in Figure 2. It is apparent that most of the high frequencies have been attenuated by the muff and that the peak pressure is lower (about 174 dB for the level 6 impulse). For the reverberant impulses, exposure was limited to one round at all levels of Tables 1 and two and three rounds only at level 6.

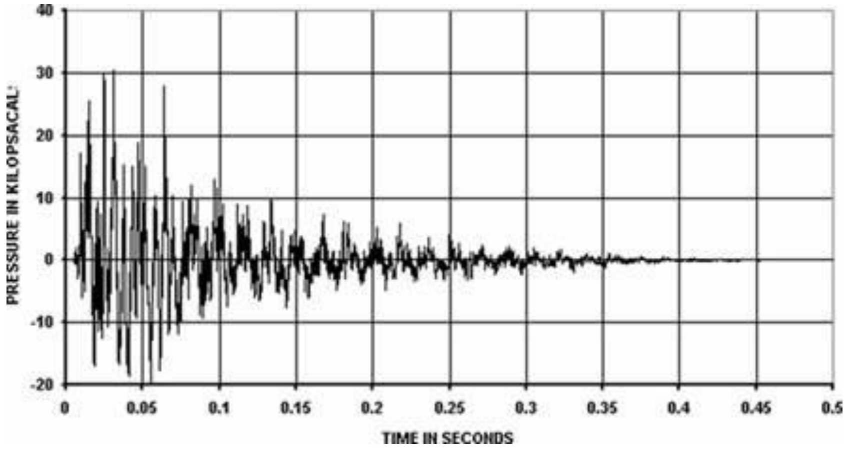


Fig. 1. Pressure history of a typical impulse in the reverberant field.

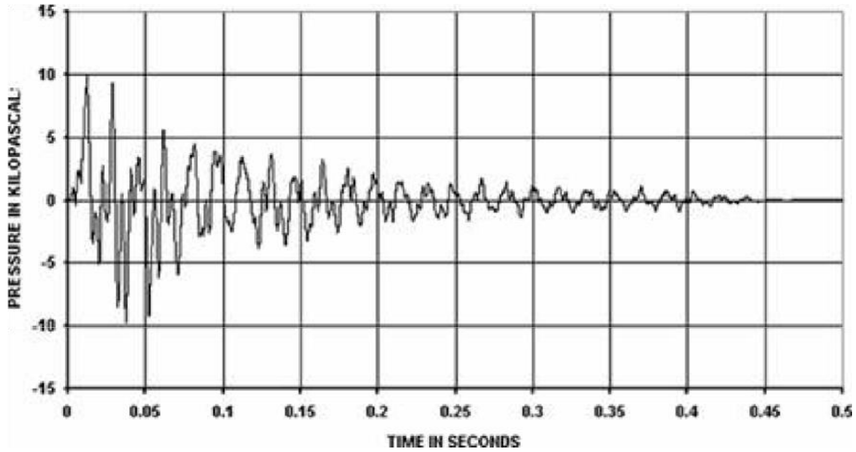


Fig. 2. Pressure history for the Level 6 reverberant impulse under the ear muff.

For the non-reverberant impulses, subjects were seated during all exposures with their heads in a chin-rest and their right ear facing the impulse source. For the reverberant impulses, the left and right ears were tested about equally. The non-test ear (typically the left ear) always wore double hearing protection. Impulses were delivered 1 minute apart following a countdown (ten, nine, eight, seven ----) that was audible because of a peak-limiting talk-through circuit in the muff. Subjects were well aware of when the impulse was coming and in fact, depended on the countdown. In one test, a set of trials was attempted without the preparatory countdown and subjects were simply unwilling to tolerate the higher exposure levels.

3. Audiometry

A baseline of thresholds was determined for each subject by automatic audiometry before any noise exposure (to be acceptable, a subject's tests had to have a standard deviation of less than 4 dB). Thresholds were determined just before exposures, then immediately afterward and changes were followed until they had resolved. Two types of "audiometric failure" were recognized in the study. Any threshold shift greater than 25 dB at any one frequency was defined as a "full audiometric failure". Threshold shifts between 15 and 25 dB, however, were taken as evidence that the ear was being stressed and the experimenters were justifiably reluctant to continue by exposing that ear to the next higher condition. These were the "conditional failures" mentioned earlier.

This level of shift was apparently well chosen. If it had been lower, then occasional audiometric variability would have given false-positive results. If higher levels of threshold shift were required, then the risk of permanent hearing loss would have been much higher. In fact, all subjects recovered to their pre-exposure thresholds.

4. The hearing protector

The Racal muff was chosen originally because it represented a moderately effective hearing protector that had a talk-through circuit and could be worn under an infantry helmet (used in the tests). It was possible that when the pressures rose to the point where the muff did not provide adequate protection, an earplug could be added and exposure continued. The unexpected result from the first 5-meter study was that the muff alone provided adequate protection for all subjects. MIL-STD-1474 had predicted that double hearing protection would not be adequate. The experimenters then made a critical decision. The seal on the right muff (toward the impulse source) was defeated when eight plastic tubes were inserted (2.3 mm inside diameter, four open to the front and four open to the rear). This leak was intended to simulate a badly fitting ear seal and perhaps more closely replicate the fit during field conditions. The 5-Meter study was rerun with these muffs followed by the 3-meter and 1-meter conditions as well as a reverberant room exposure to simulate firing from an enclosure.

5. Problems with the studies

The hearing protector. First is the question regarding the attenuation of the hearing protector. Conventional wisdom is that passive hearing protectors are essentially linear devices with respect to level, i.e., measured attenuation is independent of level. In contrast, the modified muff was non-linear with respect to amplitude, i.e. its attenuation got better as a function of level (as much as 11 dB!). And even the unmodified muff, at these very high sound pressure levels, was non-linear at the highest pressures (its attenuation became progressively worse by 5 to 6 dB at the highest level). These points are illustrated in Fig. 1 where the attenuation at each level is plotted (A-weighted SEL under the muff was subtracted from the A-weighted SEL in the free field). Free field peak pressures changed approximately 18 dB in 3-dB steps from Level 1 to Level 7. Under the muff, however, pressures rose 7.2 dB (1m data), 11.6 dB (3m data), 12.2 dB (5m data), or 15.1 dB (5m good muff).

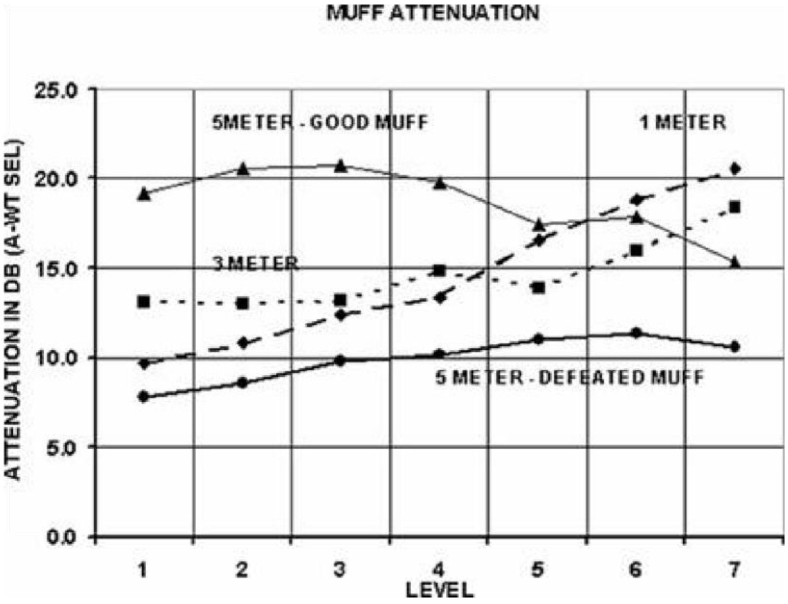


Fig. 3 Attenuation of the earmuffs used in the Albuquerque studies as a function of the exposure level. Free field SPLs increased 3 dB for each change in level. (Peak free field pressure for Level 1 was 179 dB for the 1-meter condition, 178 dB for the 3-meter condition and 173 dB for the 5-meter condition. Data from Patterson et al. (1997) and calculated from pressure histories distributed on a CD.)

An analytical technique or impulse noise standard, such as MIL STD-1474, which uses the pressure measured in the free field and/or makes a single value correction for any hearing protector obviously misses this detail in these data. On the other hand, AHAAH uses the waveform measured under the protector for its calculation and can in principle evaluate all the impulses in the Albuquerque tests without bias.

Limitations of the data set. A second concern is that we have no full exposure measured under the muff for an individual subject. We are fortunate to have the sample recordings distributed with the Albuquerque reports; however, it is not possible to follow a full exposure for any individual subject. The interest in doing a full analysis of the subjects' exposures is a function of the potential for individual impulses to have large effects, and unique circumstances in the fit of the protector or the pressure history of a specific impulse, for instance, may have had an impact on the data. By way of illustration, with impulses at these levels (as high as 195 dB peak), the forces imposed by the acoustic wave are considerable. A picture in a report by Johnson and Patterson (1993) shows a muff (one not used in the experiments) to have been lifted entirely off a manikin head about 40 msec after the initial wave front arrived. Levels above 180 dB are truly intense noise exposures and have the ability to produce unexpected effects, such as the non-linearity in Fig. 1 or movement of the muffs during the exposure (actually observed in the tests [Johnson, 1994]). Estimating the effect of 50 or 100 impulse exposures for more than 300 subjects, based on data from five or six impulses includes some uncertainty. Change in hearing at these levels sometimes occurs very suddenly, as though one impulse were particularly bad (Johnson, 1999). It is also true that sound fields around explosive sources can have occasional "hot" spots. Given the possible importance of such "rare events," it would have been interesting to have had full recordings of the exposures.

Generalizability of the Albuquerque studies. There could be overall questions as to whether the Albuquerque studies truly reproduced thecritical variables associated with real weapons exposures and whether the hazard around weapons has been truly assessed. Consider first the subjects and the muffs. The modified muff was obviously a unique device. There is, of course, neither such a thing as a "generic protector" nor any way to create a modification that correctly simulates "field fit" during all conditions and the protector, as used, was one of many possibilities. In fact, for dismounted infantry in combat it is likely that a plug will be worn rather than a muff. It is also true that all leaks should not be thought of as equal in their effect. For example, hole size and orientation could make a protector both amplitude and azimuth sensitive. Further, there is serious concern that in the experiments the protectors were carefully fitted to the subjects and they were always exposed in a specific orientation to the impulse source (ear was facing the source, holes in muff at grazing incidence). The practical hearing conservationist can only aspire to such rigorous adherence to protocol in the field in training and dream of it during conditions of combat. Finally, given the relatively high energies that were demonstrated to be tolerable in these tests, it might be tempting to assume that hearing protection "doesn't really matter" or that just any protector or modification of a protector is acceptable. Such assumptions would be disastrous.

The impulses did, to at least a first approximation, resemble those around real weapons. However, the noise field around weapons is complex and because of reflective surfaces may have unique features in every deployment. Coupled with the fact that the orientation of the Soldier is not fixed, real exposures are much more variable than the exposures in the Albuquerque studies. For example, the ground reflection of the impulse is always present for weapons fired in the open; yet because of the different geometry of the exposure situation, it was very much reduced in the 1-m and 3-m exposures. In the case of real weapons, there is usually considerable un-burnt propellant at the muzzle. Given hot propellant in a turbulent cloud coupled with sudden availability of oxygen, there may be occasional "hot spots" in the noise field because of secondary combustion where the pressures might be 10 or more decibels higher than the impulse from the muzzle. A similar caution with respect to generality applies to the reverberant impulse in the Albuquerque studies. The first several milliseconds of the impulse from a weapon fired from within an enclosure are unaffected by the enclosure. Once the pressure reaches reflective surfaces and returns, however, the latter part of the impulse becomes a function of the size of the enclosure, the reflectivity of its walls, the venting, and its specific geometry as it interacts with the active impulse source. One exposure condition hardly exhausts the possibilities and may not include critical ones.

Finally, the rate of fire in these studies was slow, about 1 impulse per minute. Soldiers are capable of firing weapons such as the 105 mm howitzer about once every 3 seconds or 20 rounds per minute (Paragallo & Dousa, 1979), and Gatling gun-type weapons can fire several thousands of rounds per minute. No one study can do everything, but it is worth noting that the rate of fire variable has not really been explored.

6. Interpretation of the data sets

Evaluating the Albuquerque data set with the AHAAH model was for the most part a straightforward exercise. The available data include digitized waveforms from subjects being exposed to almost all the conditions. Pressure histories were recorded in the free field and under the subjects' muffs for a few of the subjects and a number of the impulses. This type of data is just exactly what the model needs. The one exception is that we had no pressure histories under the muff for subjects wearing the defeated muff in the 5-m condition. Fortunately, data were available from preliminary work done with the experimenters themselves in which data had been recorded under the muff for this condition.

<u>Interpretation of failures</u>. An intuitive approach to the data sets might assume that within a data set (5-m, 3-m, 1-m, etc.) there is a similarity between all the impulses and that a failure at some given peak level would naturally imply a failure at higher levels as well. However, analysis with the model suggests that such an assumption is not warranted. Had the impulse pressure histories been identical in shape at all levels, then there would have been no question; however, the shape of the pressure history changed in significant ways as a function of level. As a result, the model's analysis indicated that the hazard from the impulses did not grow monotonically with peak level. The result was that for the 1-m and 3-m series of exposures the greatest hazard was predicted to come from the middle levels of peak pressures and actually became lower as the peak pressure rose higher. This state of affairs is presented in Figure 4 for the 1-m exposure condition, 95 percentile ear.

The basis for this inversion of predicted effect lies in the non-linear action of the middle ear coupled with the details of the waveform. In effect, the shape of the impulse following the initial peak pressure changed as pressure rose, so that the effect of the impulse was greatest in the mid-levels of the range. This interaction is discussed at some length in Appendix A. The point is that the prediction, while it may be surprising, is not irrational. If true, then it does not follow that failure at a lower level of this condition implies failure at higher levels. Thus, in scoring failures in the Albuquerque studies, failure at higher levels was not presumed unless the higher exposure level actually contained a larger number of AHUs.

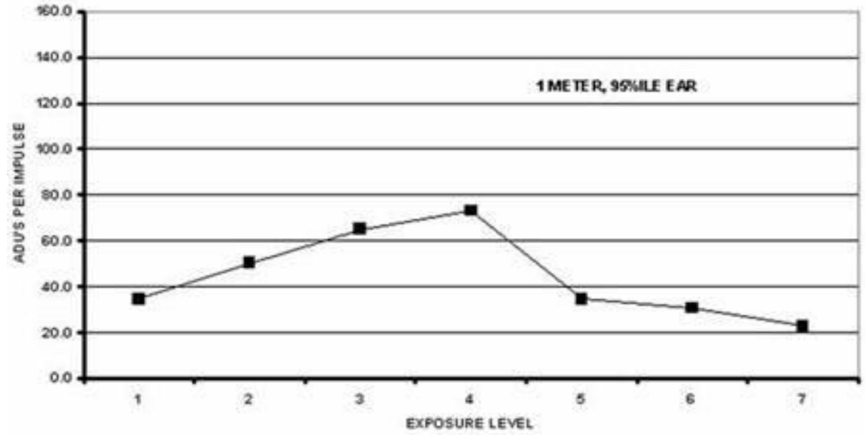


Figure 4. Plot of AHUs per impulse for pressure histories under the muff for the 1-meter exposure, 95 percentile ear.

A statistical problem inherent in the design of the study is that once a subject failed, he did not remain part of the exposure group and the group had lost its most susceptible subject. Had the impulses truly been an ascending series, then assuming failure at the higher levels would have dealt with the question of the loss of the susceptible subject. To have avoided this problem, there should have been a new group of subjects for each condition, but such an approach was simply not practical. In the end, the question of whether to consider failure at lower levels as indicating failure at higher levels turns out to be something of a tempest in a teapot. The data have been analyzed using the different approaches (see Appendix 2) and in the end, there is essentially no difference in assessment of the accuracy of the ear model's prediction.

Establishing the 95%ile failure. A statistical argument was developed (Johnson, Patterson, Nelson, Ripple, Mundie, Christensen, and Bova, 1990; Patterson and Johnson, 1994) that in a sample size of 60, one can be roughly 95% confident that the true 95 percentile subject lies between the exposures in which one and six subjects show a significant threshold shift. Alternatively put, when there is no threshold shift exceeding 25 dB, we can be 95% confident that the exposure is safe for the 95 percentile subject. Likewise, when six ears show a threshold shift of 25 or more dB, we can be 95% confident that the 95 percentile threshold shift also exceeds 25 dB. When 1 to 5 subjects show threshold excess threshold shifts, the exposure is indeterminate-- it could be either safe or hazardous. In such cases, the prediction was given the benefit of the doubt and not counted as incorrect.

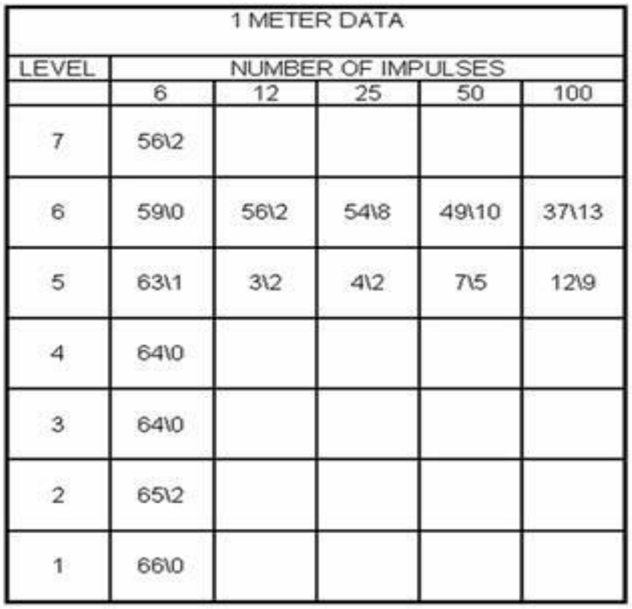
The AHAAH calculation. From the standpoint of the model, unacceptable threshold shift was predicted to occur in the 95 percentile ear when an exposure totaled 500 AHUs. Therefore, with waveforms recorded under the hearing protector, fiveor more impulses from each exposure condition (as available) were run through the model and their average was taken to be characteristic of that exposure level. The total exposure, of course, was the number of AHUs per impulse multiplied by the number of impulses. Because the Albuquerque studies included an audible countdown before each impulse, we presume that the subjects were "braced" for the event and that their middle ear muscles had contracted before the exposure. In support of this contention is the fact that the warning was very important to the subjects. When the experimenters tried one series of experiments without the clear warning, the subjects did not want to complete the exposure series.

Predictions by other methods. For comparison purposes, the predictions of MIL-STD-1474 have been calculated by Patterson et al. (1997) and are presented. There has also been an interest in using A-weighted energy as a measure of hazard, even for intense impulses (Dancer, 2000). If such a measure works, it has great advantages in measurement and in the ability to combine exposures from a variety of sources and levels, with and without hearing protection. It would also be compatible ISO-1999. For a free field measure (subject absent), the application of an 85 dB Laeq8 criterion is clear. However, where the measure is under a protector, some adjustment should be made for the fact that the measure includes higher pressures in some frequency regions because of the acoustic effects of the head and external ear. The proposal to use such an energy measure usually contains a caveat against using it above 160 dB peak pressures because of a possible critical level. This would eliminate virtually all the exposures in the Albuquerque studies even when measured under the protector. Nevertheless, it would be instructive to do an A-weighted energy calculation just to see over what range such a measure might apply. In terms of energy, an 85-dB Laeq8 exposure contains 8.7 J/m2. Exposures less than that would be rated safe; more than that, hazardous.

7. Pass/Fail analysis of the Albuquerque data

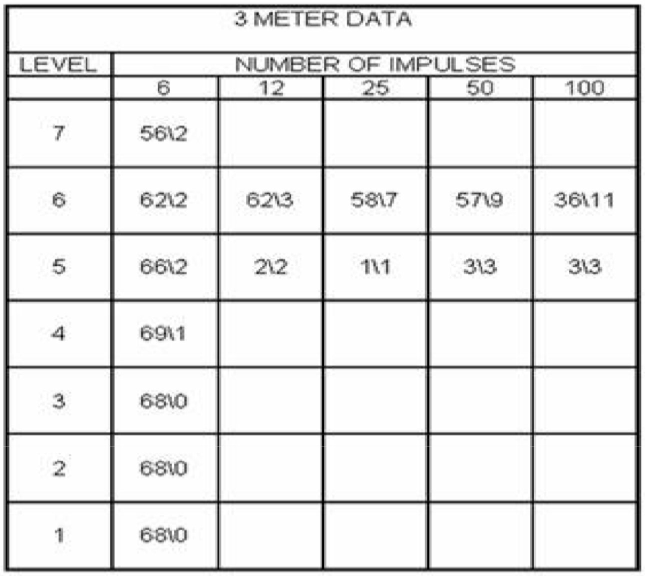
The critical question with respect to human hazard is what exposure conditions, in which 60 subjects had been tested, resulted in between one and six failures (that being the window of confidence for the 95 percentile ear). Unfortunately, these data were not immediately available; however, the exposure charts documenting each Ss path through the exposure matrix were (Johnson, 1994, Figures E-1 through E-45). Therefore, each subject's path through the exposure was individually traced. As outlined earlier, failures at lower levels were not counted as failures at higher levels unless they contained more AHUs, but within a level, failures at lower numbers of impulses were counted as presumptive failures for higher numbers of impulses.

The data summaries developed in this analysis appear in Tables II through VII which follow.



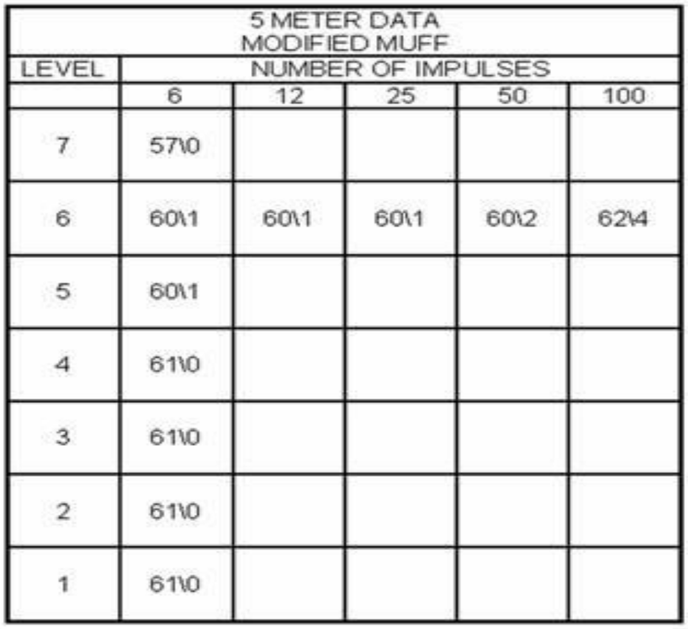
1 METER DATA					
LEVEL	NUMBER OF IMPULSES				
	6	12	25	50	100
7	56\2				
6	59\0	56\2	54\8	49\10	37\13
5	63\1	3\2	4\2	7\5	12\9
4	64\0				
3	64\0				
2	65\2				
1	66\0				

Table. II. Summary for the 1-M exposure condition (number of ears\number of failures). (These data clearly indicate a 95 percentile exposure for Level 6 between 6 and 25 impulses. The values in higher numbers of impulses in Level 5 are not large enough to be taken too seriously; however, they do represent a very high failure rate.)



3 METER DATA					
LEVEL	NUMBER OF IMPULSES				
	6	12	25	50	100
7	56\2				
6	62\2	62\3	58\7	57\9	36\11
5	66\2	2\2	1\1	3\3	3\3
4	69\1				
3	68\0				
2	68\0				
1	68\0				

Table III. Summary of tests for the 3-M condition (number of ears\number of failures). (In this case it is clear that the 95 percentile exposure for Level 6 lies somewhere between something less than 6 impulses and less than 25 impulses. The values in Level 5 are too small to be conclusive, but they do represent an extraordinarily high rate of failure and are included for interest.)

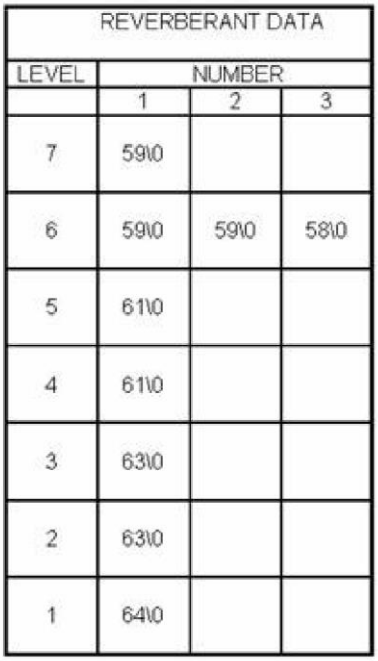


5 METER DATA MODIFIED MUFF					
LEVEL	NUMBER OF IMPULSES				
	6	12	25	50	100
7	57\0				
6	60\1	60\1	60\1	60\2	62\4
5	60\1				
4	61\0				
3	61\0				
2	61\0				
1	61\0				

Table IV. Summary for 5-M modified muff exposure (number of ears\number of failures). (The pattern of failures at Level 6 is a bit problematic. The conditional failure at L6/6 is a presumptive failure at the 12- and 25-impulse conditions, with additional failures happening at the 50- and 100- impulse conditions.)

5 METER DATA GOOD MUFF					
LEVEL	NUMBER OF IMPULSES				
	6	12	25	50	100
7	49\0				
6	58\0	56\0	53\0	44\0	39\0
5	59\0				
4	62\0				
3	62\0				
2	62\0				
1	62\0				

Table V. Summary for 5-m unmodified muff exposure (number of ears\number of failures) (in essence, no auditory failures).



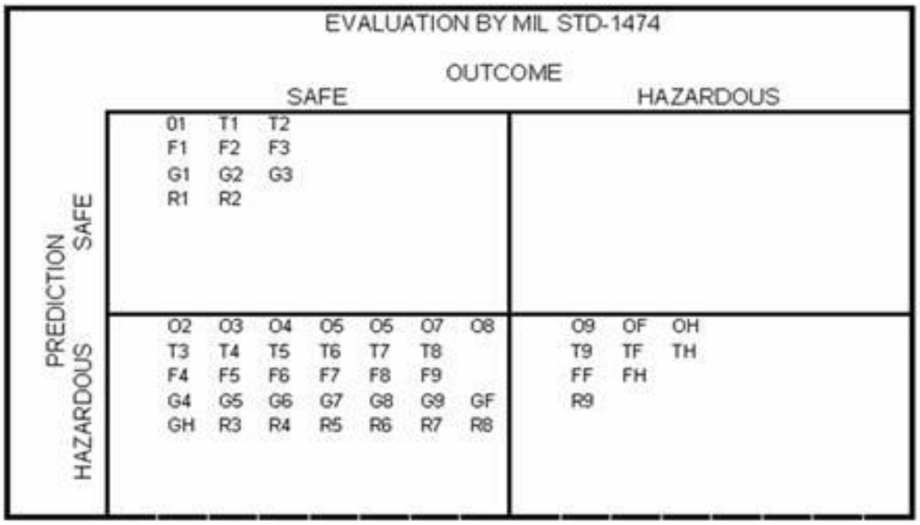
REVERBERANT DATA			
LEVEL	NUMBER		
	1	2	3
7	59\0		
6	59\0	59\0	58\0
5	61\0		
4	61\0		
3	63\0		
2	63\0		
1	64\0		

Table VI. Summary for reverberant exposures
(number of ears, number of failures).

8. Evaluation of predictions by three methods

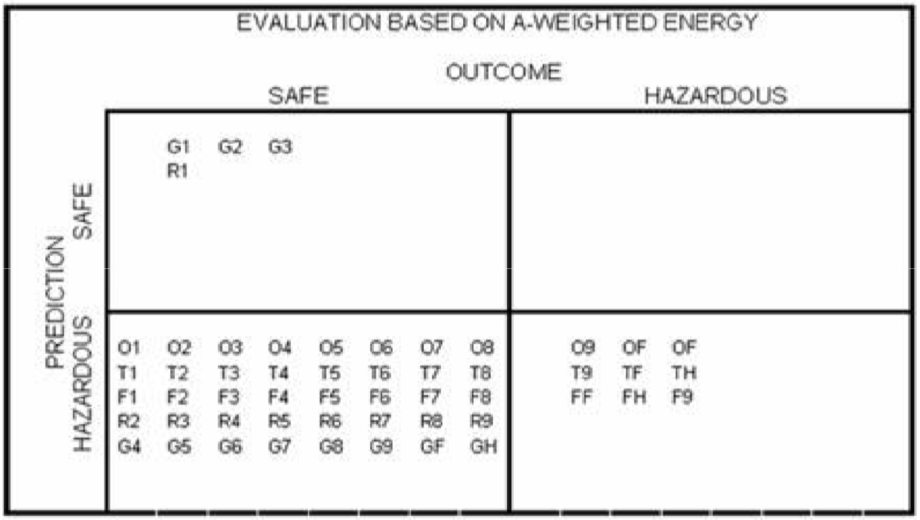
A convenient summary of the data can be seen in the following tables. In each, the predicted hazard of an exposure (either safe or hazardous) is compared with the actual outcome of the exposure (again either safe or hazardous). The criterion for hazard is a significant threshold shift in the ear of the 95 percentile subject. Evaluations by MIL-STD-1474, A-weighted energy and AHAAH are presented. The codes for the exposures listed in the exposure evaluation tables are presented in Table X.

In the following three tables, a matrix of outcomes is presented. Entries in the upper left and lower right quadrants are correct predictions (safe prediction/safe outcome or hazardous prediction/hazardous outcome). Entries in the upper right and lower left quadrants represent errors (safe prediction/hazardous outcome or hazardous prediction/safe outcome). As noted earlier, both types of error are costly and should be avoided. The entries in the table are codes indicating the exposure conditions being reported. The codes are presented in Table X.



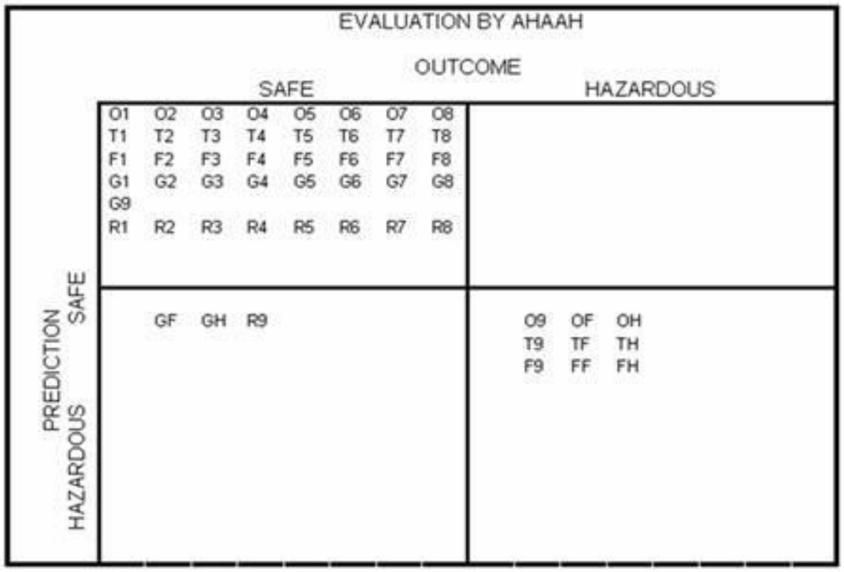
EVALUATION BY MIL STD-1474			
		OUTCOME	
		SAFE	HAZARDOUS
PREDICTION	SAFE	01 T1 T2 F1 F2 F3 G1 G2 G3 R1 R2	
	HAZARDOUS	O2 O3 O4 O5 O5 O7 O8 T3 T4 T5 T6 T7 T8 F4 F5 F6 F7 F8 F9 G4 G5 G6 G7 G8 G9 GF GH R3 R4 R5 R6 R7 R8	O9 OF OH T9 TF TH FF FH R9

Table VII. Evaluation of hazard by MIL-STD-1474. (The current MIL STD was correct in its evaluation of 20 of the exposures and incorrect in 33, an accuracy of 38%. Its errors were all in the direction of over-predicting hazard.)



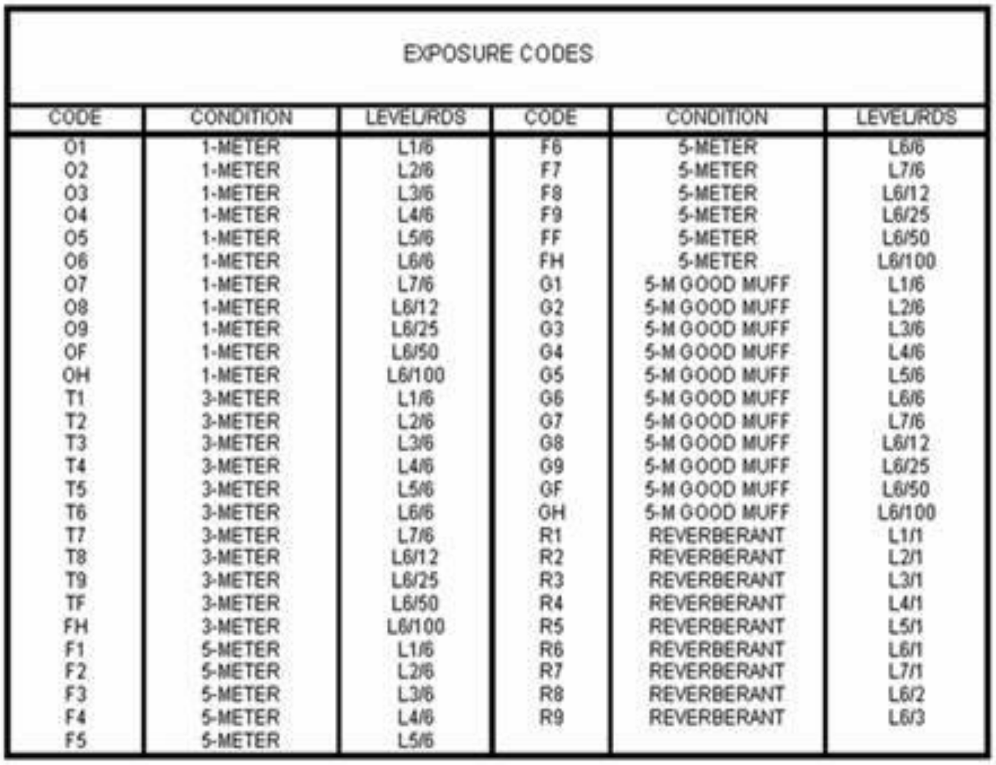
EVALUATION BASED ON A-WEIGHTED ENERGY			
		OUTCOME	
		SAFE	HAZARDOUS
PREDICTION	SAFE	G1 G2 G3 R1	
	HAZARDOUS	O1 O2 O3 O4 O5 O6 O7 O8 T1 T2 T3 T4 T5 T6 T7 T8 F1 F2 F3 F4 F5 F6 F7 F8 R2 R3 R4 R5 R6 R7 R8 R9 G4 G5 G6 G7 G8 G9 GF GH	O9 OF OF T9 TF TH FF FH F9

Table VIII. Evaluation by A-weighted energy. (A-weighted energy was successful in 13 cases of 53, an accuracy of 25%. This method erred in over-predicting the true hazard. The amount of error in the over-prediction was sizable, often 10 to 20 dB.)



EVALUATION BY AHAAH		OUTCOME SAFE	OUTCOME HAZARDOUS
PREDICTION	SAFE	O1 O2 O3 O4 O5 O6 O7 O8 T1 T2 T3 T4 T5 T6 T7 T8 F1 F2 F3 F4 F5 F6 F7 F8 G1 G2 G3 G4 G5 G6 G7 G8 G9 R1 R2 R3 R4 R5 R6 R7 R8	
	HAZARDOUS	GF GH R9	O9 OF OH T9 TF TH F9 FF FH

Table IX. Evaluation by AHAAH. (AHAAH was correct in all but three cases for an overall accuracy of 94%. Its three errors were also in the direction of over-predicting hazard.)



EXPOSURE CODES

CODE	CONDITION	LEVEL/RDS	CODE	CONDITION	LEVEL/RDS
O1	1-METER	L1/6	F6	5-METER	L6/6
O2	1-METER	L2/6	F7	5-METER	L7/6
O3	1-METER	L3/6	F8	5-METER	L6/12
O4	1-METER	L4/6	F9	5-METER	L6/25
O5	1-METER	L5/6	FF	5-METER	L6/50
O6	1-METER	L6/6	FH	5-METER	L6/100
O7	1-METER	L7/6	G1	5-M GOOD MUFF	L1/6
O8	1-METER	L6/12	G2	5-M GOOD MUFF	L2/6
O9	1-METER	L6/25	G3	5-M GOOD MUFF	L3/6
OF	1-METER	L6/50	G4	5-M GOOD MUFF	L4/6
OH	1-METER	L6/100	G5	5-M GOOD MUFF	L5/6
T1	3-METER	L1/6	G6	5-M GOOD MUFF	L6/6
T2	3-METER	L2/6	G7	5-M GOOD MUFF	L7/6
T3	3-METER	L3/6	G8	5-M GOOD MUFF	L6/12
T4	3-METER	L4/6	G9	5-M GOOD MUFF	L6/25
T5	3-METER	L5/6	GF	5-M GOOD MUFF	L6/50
T6	3-METER	L6/6	GH	5-M GOOD MUFF	L6/100
T7	3-METER	L7/6	R1	REVERBERANT	L1/1
T8	3-METER	L6/12	R2	REVERBERANT	L2/1
T9	3-METER	L6/25	R3	REVERBERANT	L3/1
TF	3-METER	L6/50	R4	REVERBERANT	L4/1
FH	3-METER	L6/100	R5	REVERBERANT	L5/1
F1	5-METER	L1/6	R6	REVERBERANT	L6/1
F2	5-METER	L2/6	R7	REVERBERANT	L7/1
F3	5-METER	L3/6	R8	REVERBERANT	L6/2
F4	5-METER	L4/6	R9	REVERBERANT	L6/3
F5	5-METER	L5/6			

Table X. Codes used in the tables evaluating the predictions of the various DRCs. (The data are all for protected hearing and are from the Albuquerque studies. All data except those labeled "good muff" were from subjects wearing the modified muff used in those studies.)

9. Effectiveness of the three methods of analyzing hazard

The evaluations with AHAAH are highly consistent with the hearing loss data in these studies (94% accurate). The three cases of inaccurate prediction (5-m, good muff, 50 and 100 impulses and reverberant room, level 6, three impulses) were in the direction of over-sensitivity.

In contrast, both the MIL-STD-1474 and the A-weighted energy measures did poorly in rating the hazard (38% and 25% accuracy, respectively). Their errors occurred in the direction of over-conservatism, which protects hearing. However, the user could pay a price in system performance if this over-restrictive approach were adopted.

A. Additional studies

Only a handful of studies are available to further test AHAAH. For a variety of practical concerns, it is understandable that over many years, only a modest amount of research has been done in which the human ear has been exposed to intense impulses. There were a few "exploratory studies" that used a variety of impulse sources to produce varying amounts of threshold shift, measured in various ways, usually with relatively small numbers of exposed subjects. The impulse was typically described by a none-too-detailed picture of a pressure history. Given that AHAAH needs a digitized pressure history to process, there are not many pieces of research in the literature that can be examined. Nevertheless, there are several challenges of the model that test its ability to predict hearing loss with both protected and unprotected exposures. They include impulses with the 7.62 mm rifle, the Belgian FNC rifle, the German G3 rifle and a 120 mm mortar. Studies using the M72 light anti-tank weapon (LAW) and spark-gap discharges, although lacking in some details also provide general tests of the fit of the model to human data. From the clinical literature we also have some indication of exposures that have produced permanent threshold shifts in human subjects. Given that each is unique, we will consider them one at a time.

In doing the hazard analyses of these impulses, the AHAAH algorithm and the A-weighted energy methods can be used. MIL STD-1474(D) does not allow any exposure without hearing protection when the peak level is above 140 dB; hence its accuracy for these impulses cannot be tested.

B. Analysis of other impulses

1. Rifle impulses: 7.62 mm

Hodge and associates at the former U.S. Army Human Engineering Laboratory (Hodge, Gates, Solderholm, Helm & Blackmer, 1964; Hodge & McCommons, 1966; Hodge, McCommons & Blackmer, 1965) conducted an extended series of pioneering studies. In those studies, the unprotected left ears of Soldiers were exposed to 25 or 50 impulses produced by a weapon firing a 7.6 2mm round at 155 or 158 dB peak pressures. There was no specific signal to the subject that an impulse was coming, but the rounds were fired at regular 5-second intervals, so it is reasonable to suppose that subjects knew when at least the second and successive rounds were coming. The reports of these studies included a careful rendering of only the initial peak of the pressure history and could not be used for analysis with AHAAH. Fortunately, we had more recently recorded several impulses from the M-14 rifle, which also fired the same 7.62 mm round. The peak levels of the recorded rounds were adjusted to those levels used in the studies. It is probably not an exact reproduction of the waveform, but we believe that it is very close to that used in the studies. Varying numbers of subjects were used (7, 12, 28) and reported the upper and lower limits, quartiles, means, medians, and standard deviations of the threshold shifts.

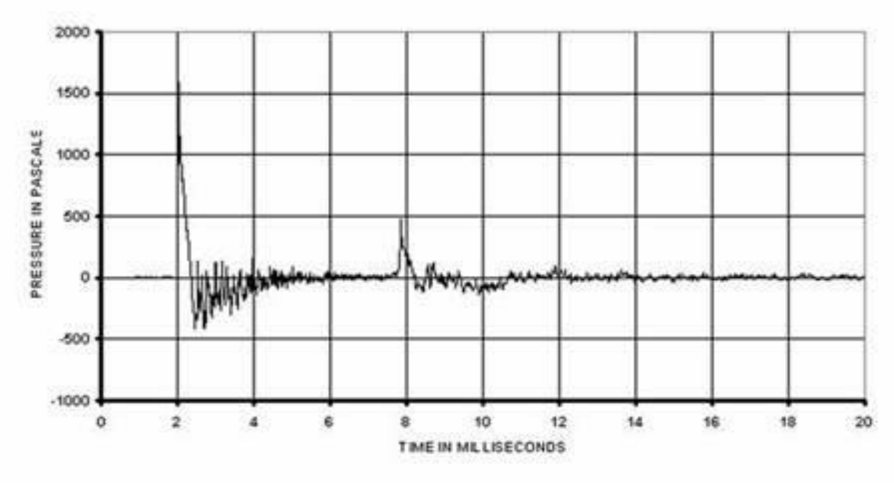


Figure 5. Pressure history of 7.62-mm rifle impulse at the subjects' ear position used in the exposures used by Hodge et al. (1964, 1965, 1966).

<u>Threshold shift data</u>. In essence, three exposure conditions, 50 rounds at 155 and 158 dB and 25 rounds at 158 dB, repeatedly produced maximum threshold shifts of 40, 50, or even 70 dB. The third quartile data in Hodge et al. (1964) were also well above 25 dB. And in other cases (Hodge & McCommons, 1966), the mean plus 1.64 standard deviations (95% of standard normal distribution) were also above 25 dB at 4 and 6 kHz. All these exposures would be rated as hazardous by the rules of the current analysis. Hodge et al also noted that 25 rounds at 158 dB produced a little less threshold shift than 50 rounds at 155 dB (no statistical test, however).

<u>Analysis with AHAAH</u>. Although there was no countdown, the timing of the impulses was regular and when the exposures were repeated with the same

subjects, the result and its variability were the same. This would argue for the use of a "warned" calculation.

<u>The 155-dB exposures</u>. The 155-dB impulses produced 16.6 AHUs/impulse (warned) and 118 AHUs unwarned. Therefore, 50 rounds at155 dB would contain 830 AHUs, which would rate the exposure as hazardous. It would also predict a threshold shift of 39 dB at ½ hour.

This falls between the third quartile (16 dB) and the upper limits of 68 and 75 dB at 4 and 6 kHz respectively (measured at 2 min) (Figure 2, Hodge et al., 1965). In terms of A-weighted energy, each impulse contained 0.27 J/M2 and a 50 round exposure, 13.5 J/M2, which would also be rated as hazardous on the basis of its energy content.

<u>The 158 dB exposures</u>. At this level, each impulse resulted in 22.3 AHUs (warned) and 153 AHUs (unwarned). This means that a 50impulse exposure would produce 1115 AHUs and a 25-impulse exposure, 558 AHUs. Both are considered hazardous. AHAAH predicts 47 and 28 dB of compound threshold shift (CTS) respectively (at ½ hour) and that is close to the result in the experiments. The study using the 50 round exposure had only seven subjects (Hodge et al., 1964), but the upper threshold shift was 54 dB temporary threshold shift after two minutes (TTS2) at 4.0 kHz and the third quartile shift was 48 TTS2 dB at 6 kHz. The 25-impulse exposure had 28 subjects (Hodge & McCommons, 1966) and the highest shift was 53 dB TTS2, with a third quartile of about 10 dB TTS2. In keeping with the conclusion of Hodge and McCommons (1966) that the 50-round exposure at 155 dB was somewhat worse that 25 rounds at 158 dB, AHAAH's analysis concurs: 830 AHUs for the 50 round exposure and 558 for the 25-round exposure.

<u>Analysis with A-weighted energy</u>. In terms of A-weighted energy, the 25-round exposure contained 13.3 J/m2 and the 50-round exposure, twice that. Both would correctly be rated as hazardous on this basis.

2. Rifle impulses: FNC rifle (5.56 mm)

Brinkman (2000) reported two exposures conducted in Germany in 1978 with the Belgian FNC rifle. In one experiment, 51 troops fired six rounds from a standing position with no hearing protection and in the other experiment, 53 Soldiers fired five rounds similarly.

<u>Threshold shift data</u>. In the first case, 11 subjects showed threshold shifts greater than 25 dB and in the second, 9 subjects showed shifts greater than 25 dB. In both cases, recoveries of these shifts took from 30 minutes to 16 hours. Given the

size of the shifts and the number of subjects showing them, both exposures would be rated as hazardous by the standard being used in this analysis.

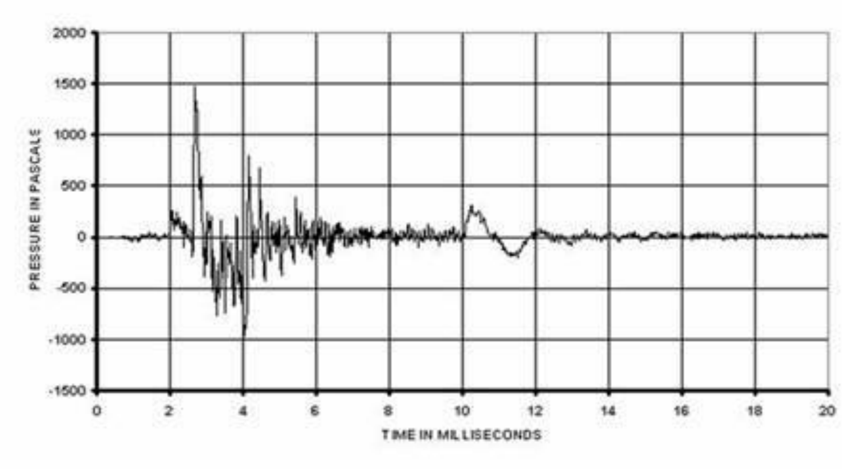


Figure 6. Pressure history of FNC rifle impulse at firer's ear position.

Analysis by AHAAH. No waveforms were available from the 1978 study; however, as part of the work of NATO RSG 29, Panel 8, Brinkmann recorded impulses from the FNC rifle for use with AHAAH. Because the Soldiers fired their own weapons, a "warned" middle ear muscle calculation was appropriate. The analysis showed an average of 156.8 AHUs per impulse (7 impulses analyzed). The two exposures would have been to 940 and 784 AHUs, respectively, both in the hazardous range and consistent with the threshold shift data.

Analysis with A-weighted energy. Each impulse contained an average of 1.4 J/m2, which means that the exposures contained 8.4 and 7J/m2 respectively. Both of these would be rated as safe on the basis of A-weighted energy. This is the only instance in which any method has rated an exposure as safe that was in fact hazardous.

3. Rifle impulses: The G3 rifle

The standard weapon in the German army was the G3 rifle. Pfander (1974) reported that as part of their training, 78 Soldiers had fired 5 rounds without hearing protection and were tested just before and just after the firing.

Threshold shift data. Pfander's method of reporting data grouped Soldiers on the basis of how long it took them to recover; thus, it is not possible to determine exactly how many Soldiers had a particular threshold shift. However, from the data reported, we can say that some Soldiers in four sub-groups had threshold shifts of 30 dB, and others in two more sub-groups had threshold shifts of 50 dB (the groups had long recovery times (3 to 6 days) and included 16 Soldiers) (Pfander, 1974, Figure 38). Clearly, this is a hazardous exposure. In fact, these data were instrumental in changing German training. This study was the last in which German Soldiers in training were allowed to fire with no protection (Pfander, 1982).

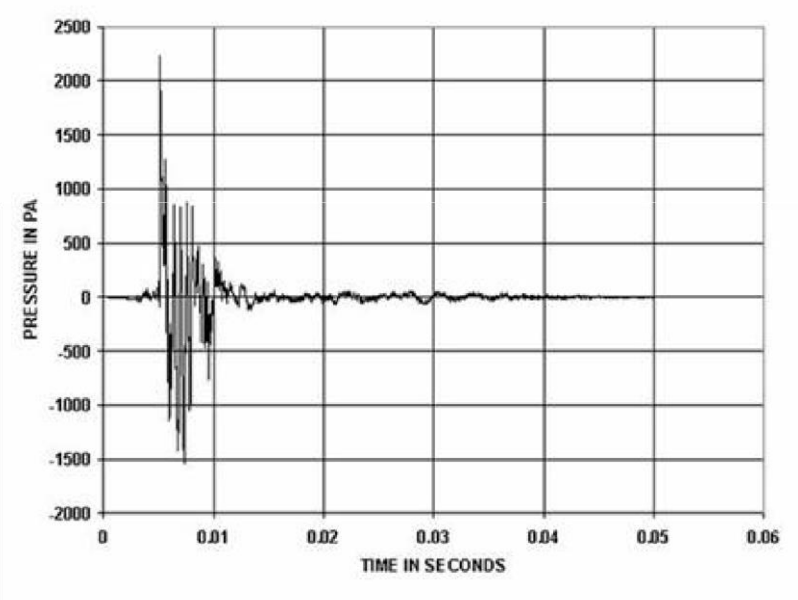


Figure 7. Pressure history for G-3 rifle at firer's ear.

Analysis by AHAAH. No pressure history from the original study was available, but as part of the NATO research study group's (RSG) work, Brinkmann also supplied an impulse from the G3 rifle for analysis that is presented in Fig. 7. In the study by Pfander, the Soldiers had fired their own weapons; therefore, a warned exposure is appropriate. The impulse contained 178.3 AHUs. In the tests, an exposure consisted of 892 AHUs, which is in the hazardous range and consistent with the threshold shift data.

a. Analysis with A-weighted energy. The G3 rifle impulse at 161 dB peak, contained 4.2 J/M2; therefore, the exposure was to 21 J/M2, which would correctly be considered hazardous.

4. M-72 Light anti-tank weapon (LAW) exposure

The following study is not an ideal test of the AHAAH model because we lack the original pressure histories and because the experimenters excluded what may have been the most susceptible subjects. However, the outcomes are not "subtle" and the data do represent a check on the reasonableness of the model's predictions in extreme cases. Garinther and Hodge (1971) and Hodge and Garinther (1970) exposed subjects with no hearing protection to an impulse from the M-72 LAW (a shoulder-fired rocket). Exposures were at grazing incidence and at a peak pressure of 161 dB, 8 m to the left and right rear of the rocket. The experimenters fired the rocket remotely following a short countdown, presumably audible by the subjects. They also allowed subjects to fire one round unprotected at the firer's position (179 dB peak pressure). The subjects had volunteered, saying that they had done the same thing before in combat (Garinther, 2000). The same study also had them fire with hearing protection (V-51R plugs, experimenter fit). The primary problem with the analysis is that we lack the pressure histories needed. We do have one digitized impulse from the M-72 LAW (presented in Figure 8), but it differs in appearance from the pressure histories reported in the studies. A second concern is that the authors note that some subjects were dropped from the study "because of slow recovery". The study had used relatively large numbers of subjects (86 ears during some conditions), but it is reasonable to suppose that the subjects dropped had the more susceptible ears, critical for an analysis seeking to identify them. Therefore, only the most tentative comparisons are warranted from these data.

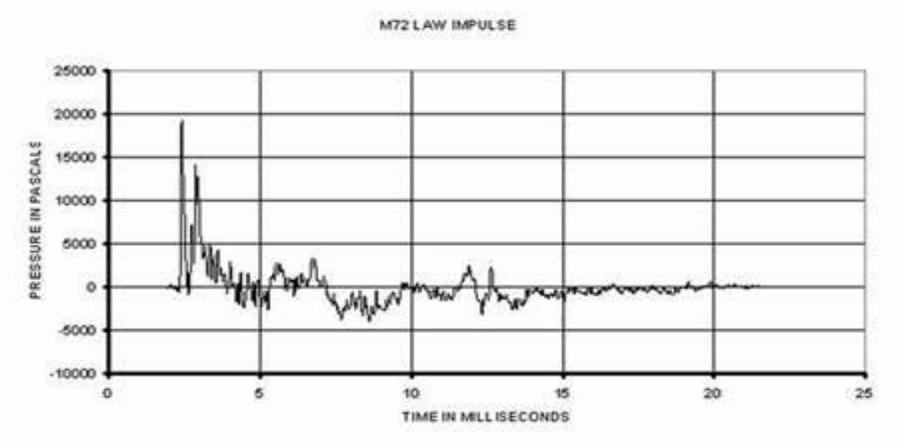


Figure 8. Pressure history of LAW impulse.

Threshold shift data. The unprotected exposures at 161 dB were within the Committee on Hearing and Bioacoustics (CHABA) limits and were interpreted as supporting the CHABA criterion (Hodge & Garinther, 1970). They would also be considered safe by the standard used in this report. It was also clear that the 179-dB exposure with unprotected ears was very hazardous, and exposures were stopped early. The protected exposures to exposures as great as 184 dB peak were shown to be safe.

Analysis with AHAAH. Given the one digitized impulse, we were able to change its apparent pressure by scaling within the computer. Real changes in pressure history would of course involve different distances with different arrival times for the ground reflections, etc. Given all the caveats, it appears that AHAAH is at least in the right "ballpark." The 161-dB impulse produced 105 AHUs warned and 516 AHUs unwarned. Such an impulse could be "just safe" as the data suggest. The 179 dB impulse produced 921 AHUs warned and 4217 AHUs unwarned, somewhere between dangerous and very dangerous (as the data suggest). AHAAH predicted 12.5 dB of CTS for the median ear 7 dB of CTS were observed. For the protected ears, AHAAH says that the firing should be safe (as it was).

Analysis with A-weighted energy. The impulse analyzed contained 1.5 J/M2 when the peak pressure was 161 dB and 114 J/M2 when at179 dB. These agree with the first being safe and the second, hazardous.

5. Mortar Impulses

This study is not an ideal test of the AHAAH model because it was primarily a test of a new non-linear earplug design worn by mortar crews. Even though the number of ears tested was small, the data were carefully collected for an intense exposure during nearly true operational conditions. The French army tested a non-linear earplug by having mortar crews (seven crews of four men) fire a 120-mm mortar while wearing the new earplug. The non-linear plug was also inserted in the ear canals of an acoustic manikin specifically designed for such tests. The plugs were designed to attenuate minimally at low sound pressure levels (>110 dB), to promote communication and situation awareness and to attenuate much more at high sound pressure levels in order to provide protection from intense impulses. The troops were professional mortar crewmen, and in the test, they fired as a crew normally does, i.e., as loader, ammunition handler, section chief, and gunner. They did fire the mortar with a lanyard (rather than just dropping the round), which means that the instant of firing was known. They fired 7 rounds (peak pressures of 185 dB at the firer's head) while wearing the non-linear earplug. The free field pressure at the firer's location is portrayed in Figure 9. The section chief and ammunition handler were exposed to somewhat lower peak pressure levels than the other crewmen. The number of subjects actually tested was relatively small (7 Soldiers at the area of maximum pressure). On the other hand, these were real troops doing their jobs, not precisely positioned, immobile subjects, which adds at least face validity to this test.

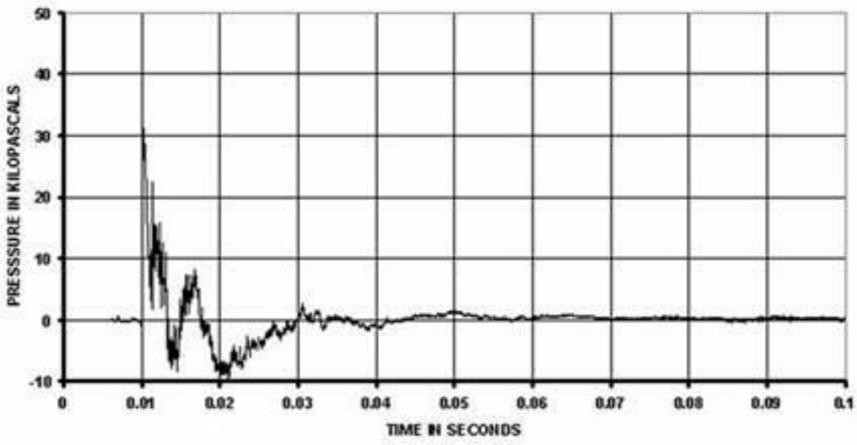


Figure 9. Free field pressure history of 120 mm mortar impulse at the firer's head location. (The peak pressure is 185.5 dB SPL.)

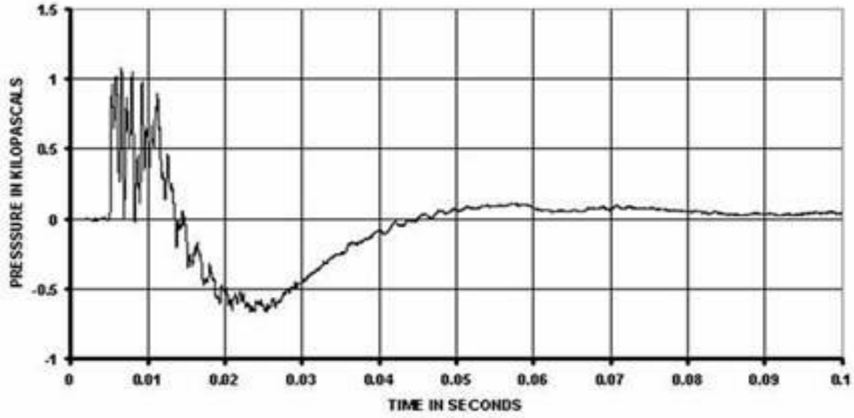


Figure 10. Pressure history of 120 mm mortar impulse at the eardrum position under the non-linear ear plug location. (Manikin situated at firer's head position.)

Threshold shift data. From the standpoint of the plug design, the test was a success because no subject experienced a significant threshold shift

Analysis with AHAAH. Digitized recordings of the pressures at the eardrum position of the acoustic manikin were made available for analysis with the ear model (Figure 10). The hazard calculated for the round in the figure was 7.2 AHUs for a warned ear and 36.8 AHUs for an unwarned ear. For a seven round exposure the total dose would have been 50.4 and 257.6 AHUs, respectively; both rated as safe exposures.

Analysis with an A-weighted energy measure. Individual impulses under the hearing protector had A-weighted energies of about 1 J/m2, the total for seven rounds being less than the 8.7 J/m2, that would have been rated hazardous. A-weighted energy would have correctly rated this exposure as safe.

Analysis with MIL-STD-1474D. Given that hearing protection was worn MIL-STD-1474(D) allows an estimate of hazard. The free field impulse in Figure 9 had a peak pressure of 185.5 dB and a B-duration of 15.6 msec, which would allow less than 1 round with single hearing protection. Since seven rounds produced no unacceptable threshold shift in anyone, we conclude that the current standard is overprotective.

6. Spark gap impulses

Loeb and Fletcher (1968) developed a spark gap impulse generator and were able to produce impulses at a 166-dB peak. By combining various numbers of gaps sequentially fired, they produced A-durations of 36 microseconds (3 gaps) to 96 microseconds (6 gaps). Subjects were exposed to one impulse per second in the free field in an anechoic chamber. The pressure histories reported in the report were detailed enough to be digitized by scanning and the fact that they were presented in an anechoic chamber meant that reflected waves were essentially not present. In terms of spectrum, the 6-gap impulse produced its peak energy at about 3 kHz, which is where the ear is tuned best and is maximally susceptible. The 3-gap impulse had its spectral peak at about 8 kHz. From a theoretical standpoint, these particular tests of the model were interesting. All the other impulses we have examined had their spectral peaks below the mid-range, which is common for most impulses in real life. So, in effect we have tested the low frequency to mid-frequency portion of the model. These two sets of impulses, however, test the mid-frequency to high-frequency portion of the model.

In these experiments, 72 subjects were tested. Exposure began with one impulse and continued with increasing numbers of impulses until a criterion shift (30 dB) had been reached at some frequency. Not surprisingly, shifts tended to be highest at 4.0 kHz and above. Because of the pattern of data taking and reporting, it is not possible to make a simple statement regarding the state of the 95 percentile ear for a given number of impulses. However, an interesting observation or two can be made. First, the 6-gap impulse was very effective at producing threshold shift. One impulse was enough for some subjects to reach the 30 dB criterion and the median subject reached it in four impulses! Secondly, the 3-gap impulse was much less hazardous; the median subject reached the criterion shift with 88 impulses.

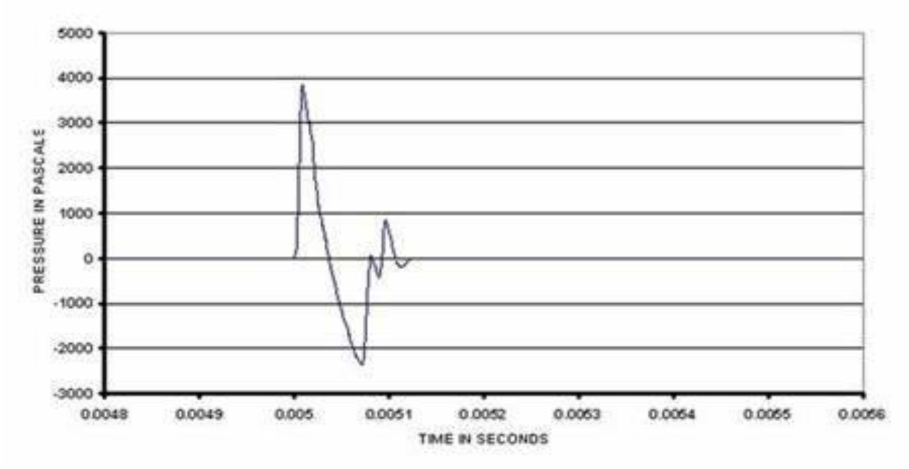


Figure 11. Pressure history of 3-gap impulse used by Fletcher and Loeb (1968).

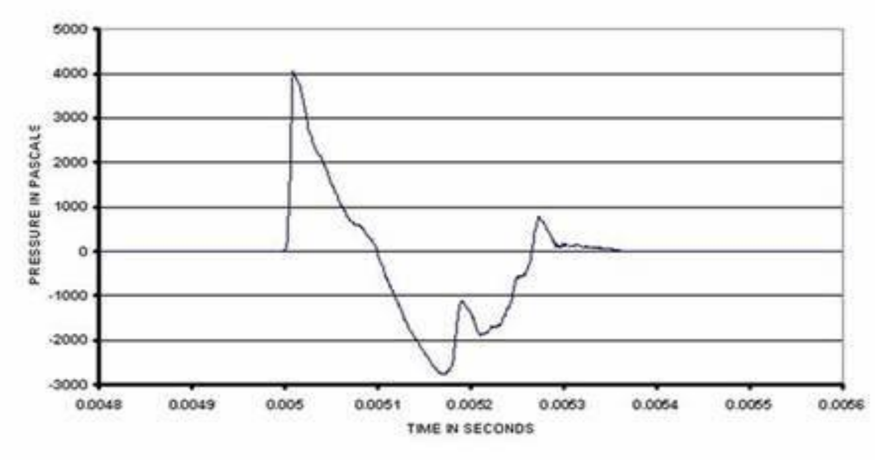


Figure 12. Pressure history of 6-gap impulse used by Fletcher and Loeb (1968).

Analysis with AHAAH. The exposures came at 1 impulse/sec. Presumably the subjects would have known just when the second and successive impulses were coming and the middle ear muscles were involved.

Each 6-gap impulse produced 176.1 AHUs (warned) and 995.4 AHUs (unwarned). AHAAH predicts that the 6-gap impulse is indeed hazardous. Thus, one impulse, unwarned, is predicted to produce 44 dB CTS in the 95 percentile ear. Even when subjects were warned, four impulses would be predicted to produce 34 dB of CTS. This is in keeping with the TTS data from Loeb and Fletcher (1968) in which they report that 0.5 impulse (!) caused a criterion shift in at least one ear. For the median ear, AHAAH predicts 56 AHUs (warned) and 342 AHUs unwarned. It is dangerously close to game playing, but we note that one unwarned and three warned impulses produce 510 AHUs (a CTS of 26 dB). Certainly, AHAAH's predictions are close to what occurred for the 6-gap impulse.

The 3-gap impulse, for the 95 percentile ear, produced 31.6 AHUs (warned) and 186 AHUs (unwarned). For the median ear, it produced 6.5 AHUs warned and 186 AHUs unwarned. Loeb and Fletcher (1968) report that a criterion shift was reached with as few as 11 impulses for this condition and the median ear reached criterion with 88 impulses. AHAAH predicts 15.6 dB of shift for a 95 percentile warned ear. If the first impulse were unwarned, the total becomes 502 AHUs, or 25 dB of CTS. AHAAH predicts for the median ear that 92 impulses would produce a 30-dB CTS--remarkably close to the 88 impulses they found.

The close correspondence between the predicted shift and the actual shift is, to a first approximation, a confirmation that the model is doing what it should at its high frequency end. On the other hand, the data of Fletcher and Loeb showed a lot of loss at very high frequencies (8 kHz to 16 kHz) (as might be expected), but the model showed less loss than occurred. It is difficult to access just what to make of this outcome. It may be that the model does not transmit energy at these very high frequencies as well as it should, or the relatively large losses may be a function of the fact that at the base of the cochlea, when a few cells are impaired, no additional cells at even higher frequencies that are available to carry information to the 8th nerve. In the middle and apical portions of the cochlea, a loss of some cells at one location can be compensated as the intensity of a signal rises and the pattern of action on the basilar membrane moves basal-ward. Once you are at the basal end, this mechanism is no longer functional and the audiometric losses grow rapidly. The test of this hypothesis would be to do the histology and discover the actual pattern of cell loss.

<u>Analysis with an A-weighted energy measure</u>. The 6-gap impulse contained 2.3 J/m2 and the 3-gap impulse 0.38 J/m2. Four 6-gapimpulses at 9.2 J/m2 fall just over the line and rate as hazardous. For the 3-gap impulse, 11 impulses contain 4.2 J/m2 and 88 impulses,

33.4 J/m2. These values are also in the right general area.

7. AT4 Exposure (antitank rocket)

There is one case in the literature that provides a consistency check on the model (Vause & LaRue, 2001). A Soldier in training inadvertently fired one round from an AT-4 rocket launcher from a kneeling position while wearing no hearing protection. He immediately experienced vertigo, tinnitus, and hearing loss so severe that he had to communicate by writing during the audiometric examination the following day. Fortunately for science, his baseline audiogram was available from his entrance physical, and of course full audiometric workups were available from the post-exposure examinations. By 21 days' post-exposure his hearing levels remained at 50 to 60 dB in the midrange and sad to say, he was released from active duty with the Army because of his hearing disability. A single case study such as this is hardly definitive, but it can be argued that an accurate hazard rating system should predict that this exposure could be very hazardous for at least a susceptible ear.

We are also fortunate to have digitized waveforms of an AT-4, recorded during weapons tests.

Analysis with AHAAH. In this case the question is whether the model predicts that such a degree of trauma could have occurred. If it pronounced the firing of one such round as safe, then it would have shown insufficient sensitivity. The waveform in Figure 13 would produce 5774 AHUs in the unwarned ear and 856 AHUs in the warned ear-- a hazardous rating in either case. However, it is interesting to note that the higher number of AHUs would be expected to produce about the PTS that in fact resulted. AHAAH appears to be in the right ballpark.

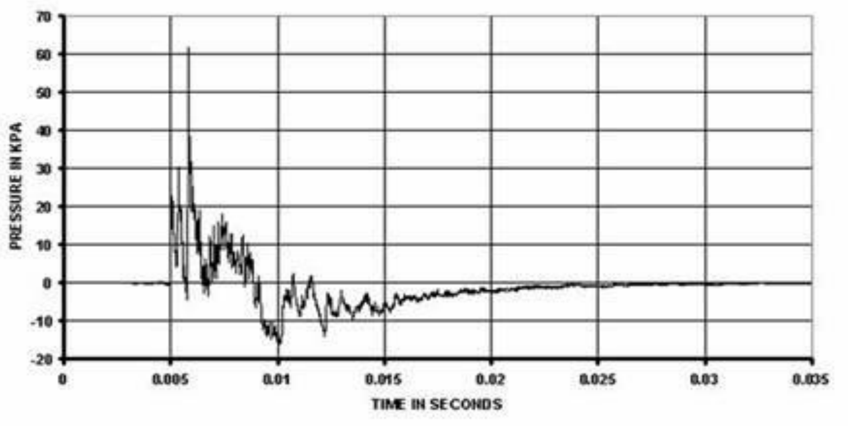


Figure 13. Pressure history of AT4 rocket firing, gunner's ear position, kneeling (Peak pressure level is 189.8 dB.)

Analysis with an A-weighted energy measure. The waveform in Figure 13 contains 783 J/m2, which is clearly in the hazardous region.

8. Exposure to a toy horn

Finally, a case has been reported by Royster, Royster, Price, McMillan, and Kileny (1999) of a 39 -month-old boy who exposed himself to several "toots" from a bicycle horn which was a small version of the classic British taxi horn (rubber bulb blowing a reed at the base of a coiled brass cone). The horn was capable of producing more than 150 dB peaks in its mouth for about 80 msec. The child immediately complained of pain and tinnitus and at 6 days showed a 50dB hearing loss (HL) in the exposed ear (HL had been 10 dB three months earlier) and at 6 months post-exposure, he had a 20 dB permanent threshold shift (PTS). The exact details of the exposure are not known (the child was playing with the horn; the parents heard the toots.) Fortunately for our purposes, we do have a recording of the horn's sound. From the standpoint of this evaluation of hazard rating methods, this case is not critical, given that it involves an indefinite exposure in one young ear (which might well be more susceptible than an adult ear) (Price, 1976). On the other hand, it would be unfortunate if a method did not indicate that such a PTS was possible from such an exposure. As reported in Royster et al. (1999), AHAAH calculated that several exposure circumstances could have produced the PTS experienced. A-weighted energy also would have considered this noise dangerous (easily having more than 10 J/m2 in the exposure).

III. CONCLUSIONS

Given all the human exposures reviewed, we conclude that AHAAH has been correct in its predictions in 96% of the cases, which included a relatively wide range of exposures: protected exposures with as many as 100 impulses at more than 180 dB under the muff as well as rifle impulses and spark gaps with no hearing protection. In contrast, the traditional methods of hazard analysis have been much less accurate. A-weighted energy was accurate in about 25% of the cases and MIL-STD-1474(D) was accurate in 38% of the cases for which it made a prediction. In general, the errors tended to be in the direction of over-rating the hazard and in the case of impulses at very high levels and with a lot of low frequency energy, the errors with the A-weighed energy measure were very large. The AHAAH model would contend that this type or error is inherent in the traditional methods of analysis because they make no allowance for the middle ear becoming non-linear at high displacements, effectively peak clipping the waveforms. Given a non-linear middle ear, then it is unlikely that any linear weighting scheme would correct this tendency to over-rate hazard.

AHAAH, in addition to being more accurate, also has the advantage of being theoretically based rather than being empirically developed. Therefore, it is more likely to correctly rate the hazard of new impulses with shapes that differ from the ones evaluated in the present report. Furthermore, AHAAH is capable of handling all sound pressures, all impulses and all exposure conditions without qualification. For example, MIL STD-1474(D), predicts only for protected ears, the use of A-weighted energy is limited to less than 160 dB peak. And if the measurements are made with a manikin, hearing protectors of all designs (both linear and non-linear) may be accommodated.

Finally, it is also worthwhile to note that because AHAAH was derived by transmutation of the model of a cat ear[1] into a model of a human ear, none of the impulses evaluated in this report were used in the development of the algorithms.

As a result, these analyses have been a true test of the model's performance on a new dataset.

Footnote

[1] In determining the accuracy of AHAA's predictions for the cat ear, established a regression line of best fit. (Price, 1998b): (26.6 x LN AHU) -140.1 = CTS in DB in which CTS = compound threshold shift, i.e., threshold shift measured about ½ hour post exposure. This function is presumed to be the generic relationship between AHUs and threshold shift for at least the cat and human cochleas; thus this formula can be used to make predictions of specific amounts of CTS for any number of AHUs. Further, the model presumes that susceptibility is normally distributed with a 6-dB standard deviation. The model adjusts for susceptibility by asserting that the susceptible ear behaves like a median ear that is being driven by a more intense waveform. This means that if the peak pressure of the waveform is reduced by 10 dB (1.64 SDs) and run through the model, loss in the 50 percentile ear can be predicted and so forth for other quartiles.

References:

Brinkmann, H. (2000). "Supplementary investigation of the German damage risk criterion with the Belgian NATO small arms rifle FNC", In: Report from NATO Research Study Group RSG.29(Panel 8 - AC/243) Reconsideration of effects of impulse noise, TNO-Report TM-00-I008, pp 6-8 (first meeting).

Buck, K., Dancer, A., and Parmentier, G. (2000). "T-weighting or A-weighting, what to use for the evaluation of exposure limits", In: Report from NATO Research Study Group RSG.29(Panel 8 - AC/243) Reconsideration of effects of impulse noise, TNO-Report TM-00-I008, pp 28-31.

Chan, P. C., Ho, K. C., Kan, K.K., Stuhmiller, J. H. and Mayorga, M. M. (2001) "Evaluation of impulse noise critieria using human volunteer data", J. Acoust. Soc. Am. 110, 1967-1975.

Dancer, A. (2000). "Proposal for a new damage risk criterion", In Report from NATO Research Study Group RSG.29(Panel 8 - AC/243) Reconsideration of effects of impulse noise, TNO-Report TM-00-I008, pp 11-15 (second meeting).

Dancer, A. (2000). "Intracochlear pressure measurements with impulse noise", In Report from NATO Research Study Group RSG.29(Panel 8 - AC/243) Reconsideration of effects of impulse noise, TNO-Report TM-00-I008, p 24

Fleischer, G. Muller, R., Heppelmann, G. and Bache, T. (2002). "Effects of acoustic impulses on hearing", J. Acoust. Soc. Am., 111, 2335.

Garinther, G.R. (2000). Personal communication.

Garinther, G. R. and Hodge, D. C. (1971). "Small-rocket noise: Hazards to hearing", Tech Mem 7-71, U.S. Army Human Engineering Laboratory, Aberdeen Proving Ground, MD. 41 pp.

Johnson, D. L. and Patterson, J. L., Jr. (1993). "Rating of hearing protector performance for impulse noise", USAARL Report No. 93-20, Ft. Rucker, AL 36362-5292.

Loeb, M and Fletcher, J. L. (1968). "Impulse duration and temporary threshold shift", J. Acoust. Soc. Am., 44, 1524-1528.

Hodge, D. C. and Garinther G. R. (1970). "Validation of the single-impulse correction factor of the CHABA impulse-noise damage-risk criterion", J. Acoust. Soc. Am., 48, 1429-1430.

Hodge, D. C., Gates, H. W., Solderholm, R. B., Helm, C. P. Jr. and Blackmer, R. F. (1964). "Preliminary studies on the impulse-noise effects on human hearing (Project HUMIN)", Tech Mem. 15-64, U.S. Army Human Engineering Laboratory, Aberdeen Proving Ground, MD. 63 pp.

Hodge, D. C. and McCommons, R. B. (1966). "Further studies of the reliability of temporary threshold shift from impulse-noise exposure", Tech. Mem. 3-66, U.S. Army Human Engineering Laboratory, Aberdeen Proving Ground, MD. 44 pp.

Hodge, D. C., McCommons, R. B. and Blackmer, R. F. (1965). "Reliability of temporary threshold shifts caused by repeated impulse-noise exposures", Tech. Mem. 3-65, U.S. Army Human Engineering Laboratory, Aberdeen Proving Ground, MD. 38 pp.

Johnson, D. (1994). "Blast overpressure studies with animals and men: A walk-up study", USAARL Contract Report No. 94-2, U.S.Army Aeromedical Research Lab, Ft. Rucker, AL 36362-0577

Johnson, D. L. (1999) Personal communication.

Johnson, D. L. (1998). "Blast overpressure studies", USAARL Contract Report No. CR-98-03, U.S. Army Aeromedical Research Laboratory, P.O. Box 620577, Ft. Rucker, AL 36362-0577.

Johnson, D. L., Patterson, J. D., Nelson, W. R., Ripple, G, Mundie, T. G., Christensen, W. I. And Bova, C. M. (1990). "Direct determination of occupational exposure limits for freefield impulse noise", Vol. III of III Appendices, Protocol for study, US Army Med R&D Command.

Kalb, J. T. and Price, G. R. Mathematical model of the ear's response to weapons impulses. In: Proceedings of the Third Conference on Weapon Launch Noise Blast Overpressure, U.S.Army Ballistics Research Laboratory, Aberdeen Proving Ground, MD 21005-5001, 1987.

NATO Research Study Group RSG.29(Panel 8 - AC/243) (2000) "Reconsideration of effects of impulse noise", TNO-Report TM-00-I008

NATO Research Study Group RSG6/PANEL8 (1987). "The effects of impulse noise", Document AC/243/(PANEL8/RSG.6)D/9, NATO, 1110 Brussels, 33pp.

Patterson, J. J. Jr. and Johnson, D. L. (1994). "Temporary threshold shifts produced by high intensity freefield impulse noise in humans wearing hearing protection", USAARL Rept. No. 94-46, U. S. Army Aeromedical Research Laboratory, Ft. Rucker, AL 36362-0577.

Patterson, J. J. Jr., Mozo, B. T., Gordon, E., Canales, J. R. and Johnson, D. L. (1997). "Pressures measured under earmuffs worn by human volunteers during exposure to freefield blast overpressures", USAARL Report No. 98-01, U.S. Army Aeromedical Research Laboratory, P.O. Box 620577, Ft. Rucker, AL 36362-0577.

Paragallo, F. R. and Dousa, W. J. Jr. (1979). "U. S. Army Human Engineering Laboratory rate of fire study", Tech Mem 9-79, US Army Human Engineering Laboratory, APG, MD. 104 pp

Pfander, F. (1982). Personal communication - date approximate.

Pfander, F. (1975). Das Knalltrauma. Berlin: Springer-Verlag