AUDITORY HAZARD ANALYSIS
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TECHNICAL REPORT 190805

Critical Analysis and Comment on Patterson and Ahroon (2004) “Evaluation of an auditory hazard model using data from human volunteer studies” USAARL Report No. 2005-01

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Abstract. Patterson and Ahroon's analysis of the AHAAH model [(2005) USAARL Rept. No. 2005-01] was evaluated. In their analysis they repeatedly failed to apply the model in a manner consistent with its premises and the theory supporting it. Thus the model was not truly tested on its own grounds; but was faulted because it did not conform to their expectations of how the ear would have responded had it behaved according to traditional expectations and been tested under many conditions not actually achieved in the Albuquerque tests (some 65% of the results they used were based on assumed outcomes). The model's results were shown to be accurate, even when counter-intuitive. The accuracy, theoretical sophistication, and analytical power of the model are unmatched by any analytical method currently available. The ancillary algorithm that created a minimum-phase digital filter designed to mimic HPD attenuation is not suited for a protector of the type used in the Albuquerque studies; therefore we agree with Patterson and Ahroon that the procedure, if used, would calculate excessively high hazards.

1. INTRODUCTION

The AHAAH model is an electro-acoustic analog of the human ear, created at the Army Research Laboratory, designed to predict auditory hazard from intense acoustic stimulation. It has been reported to be highly successful in predicting the onset of unacceptable changes in hearing, giving an accurate prediction of the threshold of hazard in better than 95% of the cases tested (Price, 2003; Price and Kalb, 2000; 1998a). This is in contrast to 36% accuracy for MIL STD-1474(d) or 30% accuracy for an A-weighted energy measure using the same human data. The model passed a peer review by the American Institute of Biological Sciences (2001) that had found it to be a significant advance in assessment technology and suitable for use as a damage-risk criterion (DRC). The model is now being used by the Society of Automotive Engineers for the analysis of hazard from airbag noise (Society of Automotive Engineers, 2003), appears as in a draft ANSI standard for impulse noise analysis (2005) and is in the process of being proposed to the Army's Surgeon General as a basis for rating hazard in the Army.

Patterson and Ahroon (2004) recently used the AHAAH model to analyze human exposure data from what has come to be known as "the Albuquerque studies" as a means of evaluating the performance of the model. They reported that they found that the model was <u>not</u> in agreement with the data from these studies. This was particularly surprising because the other analyses of these data with the same model (Price 2003c, Price and Kalb, 1998a) had come to just the opposite conclusion. Both alternatives cannot be right. Because the Albuquerque studies are the largest single set of human noise exposure data, we sought to see how these disparate evaluations of the AHAAH model's performance with this data set might be understood.

It should perhaps be noted in passing that the Albuquerque data, while important, are not nearly exhaustive or definitive where noise hazard is concerned. They bear a nominal resemblance to only four of the wave shapes encountered in practice around large caliber weapons (three in the free field and one in a reverberant space), are for protected ears only (with one uniquely non-standard protector), and are for a limited number of impulses fired at a relatively slow rate (1/min). Nonetheless, a model should be able to explain these data, which are generally characteristic of large caliber weapons.

It is significant that <u>when the model was used as designed</u>, Patterson and Ahroon's analysis was consistent with the previous analyses that had declared it accurate. The technical basis for the divergence in Patterson and Ahroon's conclusions lies largely in several traditional but unsupportable assumptions that they made regarding the nature of the Albuquerque data set and the performance of the ear. Specifically, they (1) assumed that the modified hearing protector (HPD) used in the tests was essentially linear in its operation; (2) that within any series of impulses in the Albuquerque studies, threshold shifts would grow monotonically with level; and (3) that middle ear muscle contractions could only be present when <u>evoked</u> by intense impulses rather than occur in advance of the impulses. Because these assumptions were in error, their statistical analyses and the conclusions based upon them were invalid. In addition, their conclusion that hazard grew too fast for large numbers of impulses was based on an inappropriate application of the model as well as a failure to appreciate the implications of a non-linear middle ear. Each issue will be discussed in turn.

2. THE ISSUES

2.1 The HPD.

The HPD used in the Albuquerque tests was a Racal muff. For one condition the muff was used as manufactured; however, for four other sets of tests, the seal on the muff had been defeated by installing eight relatively large holes stiffened with a plastic tubes (2.3 mm ID) so that they remained open.

The problem is that the protector's performance became a major and variable element in the exposure, accounting for almost as great a range in stimulus strength at the ear canal entrance as the deliberate manipulation of peak sound pressure level in the exposures. This point has been made on several occasions (Price, 2003c; 2003d; Price and Kalb, 1998a; 1998b) and Patterson and Ahroon (2004) even comment that " ---- the levels measured under the earmuffs suggested a non-linear growth" (p. 12). The attenuation of the muff as a function of level and exposure condition can be seen in Fig. 1. The data in this figure have been taken primarily from the report by Patterson, Mozo, Gordon, Canales and Johnson (1997) in which they reported the SPLs outside and inside

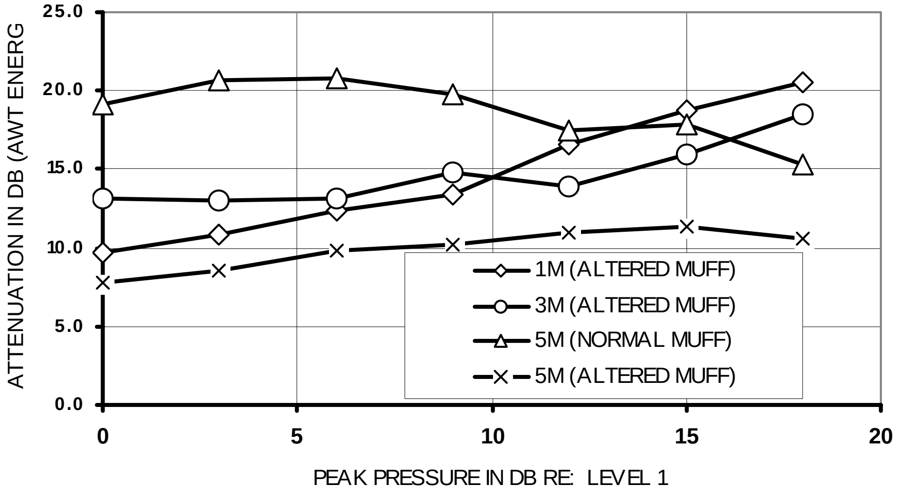

Figure 1. Attenuation of the muffs used in the Albuquerque studies for 3 different

exposure conditions displayed as a function of the test level (in dB with respect to the lowest exposure level in the tests). The base level(s) were 178 dB (1M and 3M) and 173 dB (5M). By way of comparison, there is also a line for a muff with an intact seal for the 5M condition. The designation of conditions by “M” is a convention from the Albuquerque studies and refers to the distance from the impulse source.

the muffs during the exposures and also from a CD issued by USAARL with the recorded pressure histories. The data plotted on the ordinate in Fig 1 are attenuation in A-weighted energy; but essentially the same picture would have emerged if SEL were used. There is some utility in plotting A-weighted energy given the common intuition that it might predict hazard. The abscissa is in dB with respect to the base level for the exposures. If the muff were linear in its operation all the lines would have been horizontal. The picture that emerges is quite different, however. It is apparent that the normal muff attenuated best at lower intensities (a little over 20 dB) but got worse by about 5 dB as the pressure rose above Level 3. In contrast, the altered muff for the 5m condition attenuated much less initially (just under 8 dB at level 1), but got <u>better</u> by a little more than 4 dB as the peak pressure rose. For both the 3m and 1m impulses the same pattern of improved attenuation with higher peak pressures can easily be seen. Attenuation for the 1m condition grew by 11 dB.

The reduction in attenuation at high levels with the intact muff might be expected on theoretical grounds (Buck, 2000). On the other hand it appears that the holes installed in the defeated muff progressively limited energy flow at higher SPLs; a trend that was accentuated as the spectral peak of the impulse rose (the A-duration of the impulse shortened). It would seem that the holes as configured (normal to the wave front and next to the reflecting surface of the head) were producing an effect like that seen in HPDs deliberately designed to be non-linear (Hamry, Dancer, and Evrard, 1997).

The import of these non-linearities is hard to overstate. Depending on the specific conditions, the pressure under the muff to which the ear was actually exposed, rose anywhere between 7 and 23 dB, for a nominal 18 dB change in the peak pressure of the incident waveform. Analyses cannot ignore the fact that changes in level, while they might have been 3 dB/step in the free field were truly between 1 and 4 dB/step at the ear where it mattered.

2.1.1 Implications for Patterson and Ahroon analysis.

The statistical procedures and analyses used by Ahroon and Patterson ignore the behavior of the muff as a major source of variance. Where analyses are based on pressure measured in the free field, it must be recognized that so far as the ear was concerned (under the muff) that the specification of intensity had degenerated from a ratio scale to an interval or ordinal scale and the data from the various conditions are not directly comparable, as they are portrayed in their Fig 19, for example. This source of error, when coupled with the error associated with a mistaken connection between peak pressure and loss (covered next) contaminate and invalidate the statistical analysis procedures used by Patterson and Ahroon.

2.2 Growth of Threshold Shift with Level.

Patterson and Ahroon specifically assume, in keeping with tradition, that within any series, threshold shift is a monotonic function of peak pressure level (p. 5). Therefore, when the model produced an analysis that ran counter to this assumption, it was held to be in error (p. 24). This is contrary to the basic philosophy of science. When a model, supported by theory and rational argument, makes a counter-intuitive prediction, the scientific approach would be to see whether there are data that support the prediction and if there are, then the traditional assumption has to change. Such is the case here.

Research has shown that at high sound pressure levels and relatively large displacements of the stapes (above a few microns), the annular ligament of the stapes reaches a limit of displacement that makes it act like a peak-clipper, blocking the flow of energy to the inner ear. The presence of this non-linearity has been seen in two different physical measures. Guinan and Peake (1967) optically measured, in cat, the onset of the limitation in middle ear displacement at high levels. Dancer (2000) made intra-cochlear pressure measurements in guinea pig ears subjected to increasingly intense impulses and saw the effect of peak limitation. Further, its presence was predicted on physical considerations and its implications for the human ear and DRCs have been calculated (Price, 1974). And closing the loop, hearing loss measures have also supported the effect of the clipping non-linearity with data demonstrating that higher peak pressure and greater energies do not always mean larger losses. Sommer and Nixon (1974) simulated airbag noise exposures with a low frequency pulse (simulating the filling of the passenger compartment) and a high frequency hiss (mimicking the filling of the airbag). They found more threshold shift to the high frequency pulse alone than to the two impulses combined. In essence, they demonstrated that low frequency energy modulated the flow of the higher frequency energy and the higher peak pressure of the two pulses combined resulted in less loss, the same result predicted by the AHAAH model. In a different setting Price (2003b; 1991) exposed cats to rifle impulses with essentially the same spectral shape; but greatly differing peak pressures (about 10 dB) and proportionately greater energy accompanying the higher pressure. The model made the then surprising prediction that despite the large difference in both peak pressure and energy, the two impulses would be essentially equal in effect, which is what the hearing loss data showed. Higher peak pressure did not result in higher loss. These results are also attributable to the middle ear non-linearity. Furthermore, this non-linearity has been built into the AHAAH model and is in fact largely responsible for its ability to explain the hearing loss data at high levels (Price, 2003a; Price and Kalb, 1990; 1991; 1986) while traditional criteria fail, all the while maintaining its ability to handle impulses at lower levels. Clearly, the traditional assumption made by Patterson and Ahroon needs to be rejected for the 1m and 3m elements of this dataset.

Note in passing that the foregoing argument has not maintained that the AHAAH model predicts that higher peak pressures are universally safer. For identical impulse shapes the model shows that hazard grows with increasing level, although at a decreasing rate. The problem was that in the Albuquerque studies the impulses changed shape with level and the interaction produced the apparently anomalous reduction of hazard with level for two of the conditions.

Nevertheless, while the prediction of higher hazard with lower peak pressure in two of the Albuquerque data series might be surprising, when the full analysis was considered, the prediction made good physical sense. The physical basis for the prediction is apparent once the predicted stapes displacements are analyzed (see Figs. 2 and 3).

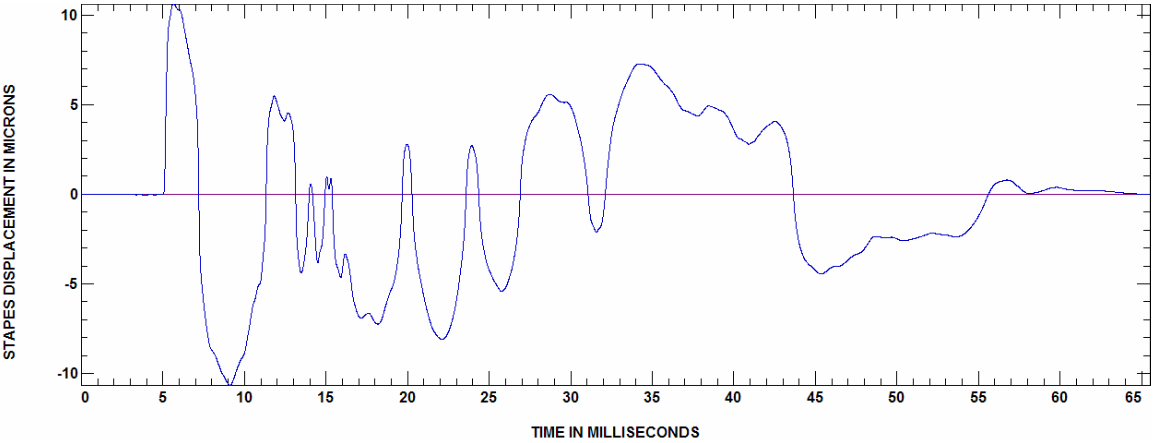

Figure 2. Calculated stapes displacement to 1m, level 4, impulse

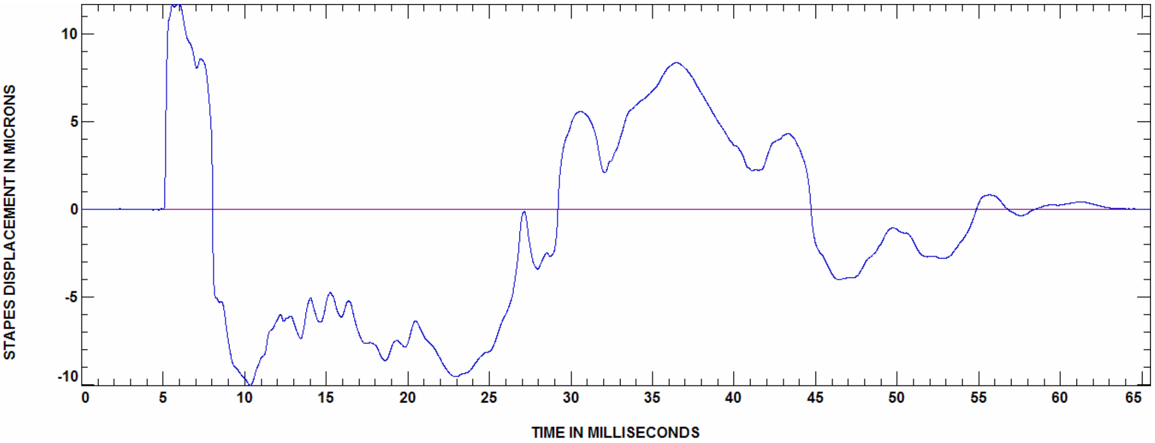

Figure 3. Calculated stapes displacement to 1m, level 6, impulse.

When we compare the calculated stapes displacements in Figs 2 and 3, we see that the model shows that the peak-clipping non-linearity has caused the stapes to really move in a greater number of driving cycles for the level 4 impulse than for the level 6 impulse and this is the basis for the greater hazard per impulse. These distinctions are apparent only in a time-domain analysis such as is done with the AHAAH model. Fortunately, for the 1m dataset, ears were tested at large numbers of rounds for both level 5 and level 6. The failure rate for level 5 was 75% (9 of 12 tested) and for level 6 was 35% (13 of 37 tested) (Price, 2003c). Though the number of subjects is relatively small, it is very important to note that the hearing loss data are consistent with the prediction. Other analyses of these data have essentially produced the same result (Chan, Ho, Kan, Stuhmiller, and Mayorga, 2001).

2.2.1 Implications for Patterson and Ahroon analysis. We conclude that one cannot assume that threshold shifts will always grow with higher peak pressures. The AHAAH model predicted that they would not and they in fact did not. This also implies that the procedure used by Patterson and Ahroon of "assuming" the data to fill out their matrices (31 data blocks available, 11 actually tested in most cases, assumptions filled 65% of the blocks) is also invalid and the conclusions regarding the AHAAH model not fitting the "data" are also without basis.

2.3 Middle Ear Muscle Contractions

Patterson and Ahroon argued that it is not reasonable to assume that the middle ear muscles were contracted at the time of the exposure and that the model should properly be used only with the "unwarned" calculation (muscle contraction elicited by the impulse which results in a delay in the contraction). Unfortunately for the purpose of this debate there are no data bearing directly on middle ear muscle activity during an actual firing exercise. On the other hand, there are data that argue persuasively that it would be reasonable to conclude that in the Albuquerque studies the middle ear muscles were contracted before the impulse arrived.

First, the studies incorporated a countdown clearly audible to the subjects. There was no question in their minds as to when the impulse was to arrive.

In the psychological vernacular, the basic question is whether or not the middle ear muscle reflex is conditionable. A number of stimuli have been shown to elicit middle ear muscle responses in man. Loud sounds, electrical stimulation, puffs of air, stimulation of the face, etc. are all capable of eliciting a middle ear muscle response. It is not just an auditory reflex; but is part of a set of facial reflexes. So in the case of intense gunfire, there are a number of unconditioned stimuli (facial stimuli) that can accompany the sound, each of which could elicit a middle ear muscle response. Unconditioned stimuli abound.

Simmons, Galambos and Rupert (1959) found that they could condition the middle ear muscle response in a waking cat. That is, once a visual stimulus was associated with a loud sound, the visual stimulus alone was sufficient to elicit a muscle contraction. But is it reasonable to suppose that the human ear would behave similarly?

The data suggest that the human ear behaves the same way. Numerous investigators with a variety of paradigms have demonstrated that the human middle ear is also conditionable (Brasher, Coles, Elwood, and Ferres, 1969; Djupesland, 1965; 1964; Yonovitz, 1976). And beyond that, the cognitive capacity of the human adds to the probability. For instance, it has been shown that middle ear muscles contracted as subjects contemplated handling a toy that was known to be noisy (Marshall, Brandt, and Marston, 1974).

Given the foregoing, it seems reasonable to us that in the presence of a clear countdown, extended experience with the paradigm, and multiple intense, unconditioned stimuli, it is only reasonable to expect the middle ear muscles to be contracted in the Albuquerque studies. Or taking the opposite perspective, how could one possibly argue that we would expect the middle ear muscles not to be contracted?

Patterson and Ahroon argue that the muscles were not contracted based on data from one experiment performed as part of the Albuquerque studies. In one set of tests the impulse could occur anywhere within a 30 second window. Patterson and Ahroon state: “there was no evidence that the volunteers’ middle ear muscles were in a warned state at the time the impulses arrived”. One can only surmise what the evidence might have been; but perhaps they expected to see an increase in threshold shifts or flinching prior to the arrival of the impulse.

The alternative explanation is that the middle ear muscles were contracted in the no-countdown experiment as well. It has the virtue of being consistent with their observation as well as harmonizing with the evidence for conditioning. It should be emphasized that the no-countdown experience was so intense and anxiety provoking for the subjects that many dropped out and the study had to be terminated before its natural conclusion. And these were experienced subjects who had already completed a full series of the same impulses with a countdown. If Marshall et al. (1974) were able to measure middle ear muscle responses when people <u>contemplated</u> a toy “reputed” to be noisy, how much more likely is it that middle ear muscle responses would have been present as the subjects contemplated an exposure to impulses intense enough to be distinctly unpleasant with which they had considerable experience? The reasonable conclusion would be that middle ear muscle responses were in fact present in all cases and so no differences would be expected, which is what they observed.

A parallel set of observations supports the same conclusion. In earlier experiments, the same question of middle ear muscle activity arose as waking cats were first exposed to weapons impulses (Price, 1983). Variable timing of impulses was used to make a conditioned response less likely and high-speed motion pictures revealed no evidence for anticipation of the arrival of the impulse. Nonetheless, when the animals were deliberately anesthetized during the exposure (inactivating the middle ear muscles chemically) much greater losses were seen (Price, 1991). The conclusion was that middle ear muscles should be presumed to be active nearly continuously during such exposures with waking animals, even though there was no outward sign that they were.

<u>2.3.1 Implications for the Patterson and Ahroon analysis.</u> Patterson and Ahroon’s argument that the muscles were not contracted ignores the literature on middle ear muscle activity and misinterprets the Albuquerque data. The most parsimonious explanation is that the middle ear muscles were contracted at the time of the exposure.

2.4 Growth of Hazard with Increasing Numbers of Impulses

Patterson and Ahroon argued that the growth of loss as predicted by the AHAAH model was much too rapid for large numbers of impulses. This contention is largely the result of the problems noted in the foregoing sections (e.g. ignoring the effect of the HPD, assumptions regarding growth of hazard with level, the use of 65% assumed data, middle ear muscle state miscategorized, etc.). There are yet two additional concerns regarding the (mis)application of the model. Given their description of what they did to see the effect of increasing numbers of impulses (multiply the number of ARUs per impulse by the number of impulses), their procedure gave the predicted hazard <u>for the 95%ile ear</u>, for the case in which stimulation were increased in level up to the permanent hearing loss in the ear. The relationship between ARUs and threshold shift was in fact established in this fashion with animal ears where permanent hearing loss could be produced. There are of course no human data of this type to serve as a basis for Patterson and Ahroon to make such a comparison. In practice, in the Albuquerque studies, exposures were stopped for individual ears once a 15 dB shift was reached or exceeded so as to prevent the possibility of permanent hearing loss. In those studies the available human data were therefore for the percentage of the population reaching that threshold level. The model can be used for such a calculation by changing the susceptibility of the ear for which the calculation is being done and then calculating the function relating number of rounds to percent of Ss reaching the criterion. If one does that with the Albuquerque data, the rate of growth of loss is indeed a little faster than the rate actually seen; but not unreasonably so. On the other hand, the rate of presentation in the Albuquerque studies was relatively slow (1/min). In practice, a single 105 mm howitzer is capable of firing about 20 rounds/min and if and entire battery were firing, the exposure would be proportionately greater. If indeed there were some recovery process operating between rounds at the slower rate used at Albuquerque, then perhaps the model's calculation of a slightly higher rate of loss is in the right direction. Given this possibility, it would be protective of human hearing to assume that for exposures occurring more rapidly (the type on which the model was initially validated) the rate of growth of loss might be somewhat higher than they saw in the Albuquerque studies. Additional data on this point might provide the basis for an improved model.

A second problem with the Patterson and Ahroon analysis regarding the growth of hazard with level and number of impulses is hidden within the basic data regarding the ear's function. In their report they use the concept of the level/number trading ratio to generate expectations regarding the model's outcome. The concept has long been used (Smoorenburg, 2003); but as a result of the non-linear conductive path in the middle ear, it suffers a fatal conceptual flaw. Because the conductive path changes, there can never be a generalized single level/number trading ratio applicable at all levels. The problem is illustrated in Fig. 4 in which, by way of illustration, an airbag impulse was manipulated digitally to assume a wide range of peak pressures and analyzed with the AHAAH model. We see in the figure that the number allowed falls as the pressure rises, as we would expect. Note that the level/number trading ratio varies from 10 at lower levels (essentially an energy relationship) to a little over 2 at higher pressures. Depending upon where you are in the pressure regime, the level/number trading ratio could be anywhere between about 2 and 10 a finding in keeping with calculations seeking a level/number trading ratio (Smoorenburg, 2003). The data in Fig. 4 are for a particular pulse; but the point is that on theoretical grounds one cannot assume that there is a single level/number trading ratio that applies to impulses in general at all levels. It is on these grounds that A-weighted energy simply must fail as a general rating rule at high sound pressures (Price, 2003c). And on these grounds, the Patterson and Ahroon analysis suggesting that the model's output is incorrect because it does not follow data they project would exist, if measured, based on a particular level/number trading ratio.

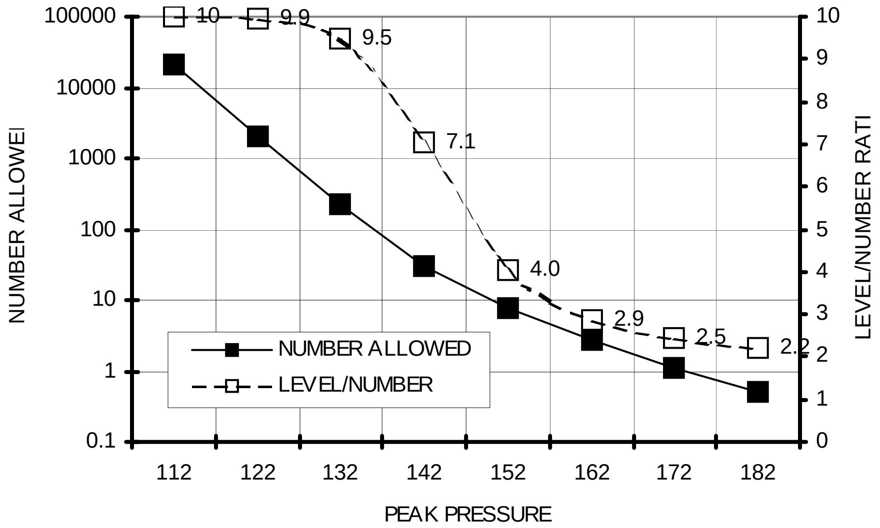

Fig. 4. Number of impulses allowable as a function of level for the same impulse with varying peak pressures. Also plotted on is the level/number ratio as the peak pressure changes.

2.4.1Implications for the Patterson and Ahroon Analysis Their assertion that the growth of hazard was too rapid for large numbers of impulses is based on a misuse of the model. The predicted growth and actual growth are reasonably close when properly calculated. Furthermore, the basis for portions of the analysis based on an assumed level/number trading ratio can be rejected as not in line with theory or empirical measures of the ear's function.

3. ANOTHER ISSUE – THE MINIMUM PHASE ATTENAUTION CALCULATION

The AHAAH model has in some cases been provided with an accessory feature that consists of algorithms that allow the specification of attenuation(s) at various frequencies, as for an HPD. An algorithm creates a digital filter that produces that attenuation at those frequencies and the input waveform is processed through it. Ideally, one could specify the attenuation for any linear HPD and see the effect on the pressure history of the waveform. Such an algorithm would be useful in allowing computation of the effect of any HPD on risk from an impulse noise.

This feature was included with the AHAAH model as an exploratory tool rather than as integral part of the model. It makes use of a minimum-phase calculation, which by its nature assumes that there is only one conductive path through the system being modeled. As we have seen that is clearly not the case for the HPD used in the Albuquerque studies. And there is even a reasonable question as to whether or not such a characterization fits muff type protectors or for that matter even insert protectors. Models of HPDs typically include conductive paths through the shell of the muff or plug, leaks past the seal, as well as paths through the seal and tissue in the vicinity of the ear canal (Shaw and Thiessen, 1962; Schroter, 1983; Zwislocki, 1957). As in the case for the use of A-weighted energy as a hazard-rating tool, it is not that there is an overwhelming case *for* the procedure; but the simplicity of the idea is so beguiling that one applies it in the *hope* that it will be useful.

In the small number of attempts that we have made to test the use of the minimum phase calculation we have found that the ARUs calculated with the procedure tend to be higher than those calculated from a waveform measured under a protector.

Therefore in this paper, where we may disagree on a number of grounds with Patterson and Ahroon's calculation of hazard with the minimum-phase procedure, we do agree with at least the direction of the outcome – the hazard, in ARUs, tends to be too high. Electro-acoustic models of HPDs that actually follow the conductive paths would be expected to reproduce HPD effects on a waveform more accurately.

4. GENERAL DISCUSSION

As an electro-acoustic analog of the ear designed to predict hearing loss, the AHAAH model is in fact a theory of hearing loss. In scientific discourse, when a theory is evaluated, it is customary to grant its premises and then follow the trail of implications. A theory should make predictions that are testable and if it provides power not previously available, then it should be used in preference to other theories that have less predictive power.

In fact the Patterson and Ahroon report promised to be "an evaluation of an auditory hazard model –"; but it has fallen far short of its stated intention. In effect it neither accepted nor effectively contested the basic premises of the model. They simply proceeded to evaluate the AHAAH model according to existing assumptions and practice, procedures that have long proven to be inadequate to handle the complexity in the data. And when the model did not agree with the analysis based on failed procedures, the model was held to be in error. As we have seen, just the reverse conclusion should be drawn -- the model is fine, traditional practice is wanting. When the model was used in a theoretically consistent manner, and at times within Patterson and Ahroon's analysis, it proved to be accurate, even when the predictions seemed counter-intuitive.

Further, the difference in accuracy between the AHAAH model and traditional measures of hazard – the ability to establish the onset of hazardous exposure in the 95%ile subject – is immense. The AHAAH model has been shown to be accurate in 94% of the cases for the Albuquerque dataset as compared to 36% and lower for existing hazard rating methods. The failure claimed by Patterson and Ahroon has not been that of the model, but of their inappropriate use of the model in their analysis.

The AHAAH model has received public scrutiny. It was developed and shared during the tenure of two NATO RSGs on impulse noise meeting over a period of almost 20 years (NATO, 1987; 2000). The US Army Aeromedical Research Laboratory was a member of that group as were virtually all the free world's experts on military impulse noise. It has also been demonstrated to perform accurately for the Albuquerque data set to a peer review established and financed by the US Army Medical Research and Development Command (American Institute of Biological Sciences, 2003). It has been presented to national and international technical meetings (e.g. Price, 2003a; 2001; Price and Kalb, 1998b). In addition, the data and these analyses have been available to the scientific community (Price, 2003c; 2003d). Further, the AHAAH model has worked its way though the peer review processes of the Society of Automotive Engineers and has been accepted as the basis for analysis of airbag noise in automobiles (SAE, 2003).

The Patterson and Ahroon analysis limited its consideration of the AHAAH model to its application to the Albuquerque data set. In a more comprehensive evaluation they might have also considered other significant aspects of the model and commented on them. For example, the model reproduces transfer functions that have been measured for the human ear - both in magnitude and in phase. The fact that the model matches this large dataset assures the user that the conductive path to the inner ear contained in the model is consistent with what is known about human hearing. In fact the model brings with it additional benefits that extend well beyond the Albuquerque data set.

The model's strong theoretical basis has allowed hazard prediction to make a major move in the direction of achieving generality. Approaches that are simply correlational, e.g. using peak pressure as an index of hazard, can be applied with confidence only with the dataset on which they were generated. In a strict statistical sense the Albuquerque data set is not really like any particular weapon system and the hearing protector used in it, as we have also seen, is highly idiosyncratic. Any use of correlations between peak pressure and hearing loss as a means of predicting hazard is a perilous and an ill-advised extrapolation. On the other hand the AHAAH model is not so limited. Because it can use pressure at three locations (free space, ear canal entrance or ear drum) as input and calculates the ear's response from that, its approach is general and not dependent on the particular qualities of any impulse or the source that generated it or, if pressures are measured under the muff, the nature of the muff protector. Of course, as is true for all theories, its accuracy should be reexamined as new data become available; but it is extremely important to note that because of its foundation in theory, we have a reasonable expectation that its answers will be accurate for new impulses. This versatility of the model has already been demonstrated when the model, without changes or special assumptions, was used to rate hazard for unprotected exposures to rifle fire, spark gap discharges, shoulder fired rockets, etc. (Price, 2003c).

Patterson and Ahroon also did not choose to evaluate or comment on other features of the model, such as the movie it makes relating measured acoustic pressures to displacements in the cochlea. This feature, unique to the AHAAH model, provides the possibility for engineering insight into the action of sound within the ear. For instance, in analyzing airbag noise in a closed passenger compartment, the AHAAH model pointed out that the majority of hazard in the impulse was a function of one portion of the waveform that was the result of the way that the bag deployed mechanically (Price, 2005). Damping the bounce in the bag's physical deployment, with no change in the filling noise, would have made a hazardous impulse into a safe one. This feature, coupled with the theoretical basis of the model, creates a powerful analytical tool for use by weapons designers who need to create longer range, more powerful, more accurate, weapons that are also safe to fire.

Furthermore the model is designed for and essential to evaluating modern hearing protective devices, an acute need in the modern army. Experience in battle indicates that the modern soldier needs adequate hearing protection that allows him/her to maintain communication and situation awareness as well. Many HPD designs are possible, some using new principles; but how are we to evaluate the effectiveness of the protector? Measures such as A-weighted energy, in vogue in much of the world, have been shown for large caliber weapons to be grossly in error with data from the Albuquerque studies (Price, 2003c). And MIL-STD-1474(d) makes no differentiation between protectors. The AHAAH model, on the other hand, provides a nearly ideal vehicle for the design and analysis of virtually any type of HPD. It accepts inputs at any achievable location and in turn provides an interpretable output of the effect on the ear to include a numeric as well as a visual portrayal of the evolution of hazard in the inner ear. This feature of the model is critical for HPD development and has already been used in the exploration of HPD issues (Jokel, Kalb and Sachs, 2005; Price, 2001).

A final feature of the AHAAH model that is important is that it is available now. The absolutely perfect analysis tool is undoubtedly still to be developed. The model might some day include adaptive middle ear muscles and provisions for allowing for the beneficial effects of quiet intervals, etc. And it could be modified to incorporate such changes. Yet decisions critical to the Army and the nation's welfare are being made as this is written and they need the benefit of the best scientific advice presently available. For now and the foreseeable future the AHAAH model is the best tool available.

5. CONCLUSIONS

The evaluation of the AHAAH model by Patterson and Ahroon (2004) produced nothing inconsistent with previous analyses that found it to be accurate, when they used the model as it was designed.

On the other hand, their primary analytical approach required them to assume data that would have been present in the data matrices of the Albuquerque studies had they actually been tested (about 65% of the data in their analysis was assumed). To arrive at these assumed data, they had to (1) posit that the HPD used in the tests was linear with respect to amplitude and behaved similarly for all conditions, (2) assert that all threshold shifts must grow monotonically as a function of peak pressure, and (3) hold that the middle ear muscles would only contract after the impulse is present and not in anticipation of the impulse. Data from a variety of sources argue persuasively that these three assumptions underlying their analytical approach are not tenable. In addition, their conclusion regarding the model's prediction of the rate of hazard growth was shown to be based on a misapplication of the model and a failure to follow the implications of a non-linear middle ear. As a result, the negative findings reported by Patterson and Ahroon can be understood to be the result of an improper use of the model and not a test of it. In the end, the AHAAH model's accuracy remains far better than any other approach.

Patterson and Ahroon’s analysis of the model also overlooked the critical benefits that accrue from the model’s design: (1) increased generality of application, (2) the availability of an intracochlear movie to provide engineering insight and (3) the ability of the model to serve as a design tool for HPD design and evaluation.

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