Impulse Noise and the Cat Cochlea

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Abstract

As a step in the development of a theoretically based mathematical model of auditory hazard from intense sounds for the human ear, we first developed a model for the cat ear which could be tested with damaging impulses. This paper reports the results of 6 of the 12 exposures used. Cats were anesthetized (to eliminate middle ear muscle activity) and exposed at different locations to impulses produced by the US Army's M-16 rifle. Peak pressures ranged from 140 dB to 170 dB with 1, 6, 12, or 50 impulses in the exposure. Immediate and permanent losses were established by brain-stem audiometry at octave intervals from 1.0 to 16.0 kHz. When losses were analyzed from the 12 exposures, the correlation with A-weighted energy in the exposure was very poor. When the model was used for the analysis, the overall correlation between its prediction and the immediate loss was 0.94. The implications from the model are (1) that the cochlea is damaged very quickly once intracochlear displacements reach a critical level, (2) the external and middle ears 'shape' the energy arriving at the cochlea, and (3) a peak-limiting, non-linear, middle ear protects the cochlea from very large displacements.

I. INTRODUCTION

Predicting the hazard from intense impulsive sounds has proved to be an intractable problem (NATO, 1987; Smoorenburg, 2000). Most attempts at generating predictive schemes have been essentially empirically based attempts to fit sound measures to hearing loss data. In such approaches the ear is essentially represented as a "black box," and attention is focused on novel ways of analyzing the acoustic exposure. We chose to focus our efforts on "opening the black box" by determining the basic mechanisms operating in the ear in response to intense sounds and then to create algorithms that would predict hearing loss. The center of this effort has been our development of a mathematical model of the human ear designed for this purpose (Kalb & Price, 1987; Price & Kalb, 1991; Price & Kalb, 1998). Given the great similarity between mammalian ears, we elected to model the cat ear first, which could actually be tested with exposures to impulsive sounds at hazardous levels. Once it was clear that the model was predicting hearing loss properly, we proposed to create a parallel human model using the insight gained from the work with the cat ear. In all, 12 different exposures were used. Of these, six have been reported earlier: three different exposures to airbags (Price & Kalb, 1999) and three different exposures to impulses from a primer (Price & Wansack, 1989). This paper reports six previously unpublished exposures of the cat ear to various impulses produced by a rifle (Pierson, Price, Kalb, & Mundis, 1995).

II. DESIGN OF THE EXPERIMENTS

A. Exposure conditions

When the primary interest is in modeling the cochlea's response to intense sound, middle ear muscle activity presents a problem because it represents an essentially uncontrolled attenuator in the conductive path that can affect sound transmission by 20 or more decibels. Pilot studies convinced us that the cat must normally have its middle ear muscles active most of the time, not just in response to intense stimuli (Price, 1991). We had sought evidence from movies made of cats being exposed, thinking that they might have shown evidence of a "flinch" before the impulse arrived (Price, Kim, Lim, & Dunn, 1989). There was no visible sign that they anticipated the impulse. When cats were anesthetized at the time of the exposure to eliminate middle ear muscle activity, they sustained very much larger losses (both TTSs and PTSs) than those not anesthetized at all or those anesthetized immediately after the exposure (to control for the presence of anesthesia) (Price, 1991). This outcome agrees with the work of Simmons (1959) who had recorded cochlear microphonic output from waking cats and concluded that the waking cat has its middle ear muscles active most of the time.

Exposures in the present studies were therefore done with anesthetized animals, which not only made it possible to position and test them but also to deactivate the middle ear muscles (Simmons, 1960). The losses were then a function of the sound field, the conductive path through the middle ear and intracochlear processes, unclouded by middle ear muscle responses.

B. Stimuli

All the stimuli described here were produced by the M-16 rifle, the primary infantry weapon of the U.S. Army. It had the advantage of being a true explosive noise source, highly repeatable, and readily available. From the perspective of experimental design, exposure conditions were chosen that were interesting from a theoretical standpoint, which would be severe enough to produce loss in at least some ears but not so severe that they would produce total loss in all ears. An exposure producing no loss tells you only that it was safe but not how safe, and total loss demonstrates the opposite point.

1. "Traditional impulses" at a modest level.

In two exposures, the exposure location was at 90 degrees to the line of fire. The pioneering work with human ears and impulse noise exposure by Hodge and his colleagues (1964, 1965, 1966, and 1967) used essentially this location because it provided a pressure history resembling the classic Friedlander waveform. Distances from the muzzle were chosen so that the peak pressures were 140 and 145 dB. The pressure histories at these locations area presented in Figures 1 and 2. These impulses were intended to be typical of impulse noises produced by explosive sources and at a level where 50 impulses would produce a measurable threshold shift in the cat. For the 140-dB impulse, the A-weighted energy1 in the impulse was 0.009 J/m2 and for the 145-dB impulse it was 0.027 J/m2. It would have been desirable from a theoretical standpoint if the waveforms had been identical in the shape of their pressure histories; but the physics of sound transmission over the ground interfered. At the distance necessary reduce the peak pressure to 140 and 145 dB (about 11 and 20 m from the muzzle, respectively), the ground reflection of the impulse interacted with the impulse conducted directly from the muzzle and changed the waveform slightly. The result was that the A-duration of the 145-dB impulse was 435 microseconds and for the 140 dB impulse 295 microseconds. By way of comparison, at the position of the firer's ear the reflected pulse is clearly visible as it follows the direct path by about 8 msec (Figure 3) and the A-duration of the primary impulse was 350 microseconds. This change in impulse shape proved interesting because it was accompanied by a change in effect that will be discussed when the threshold shift data are presented.

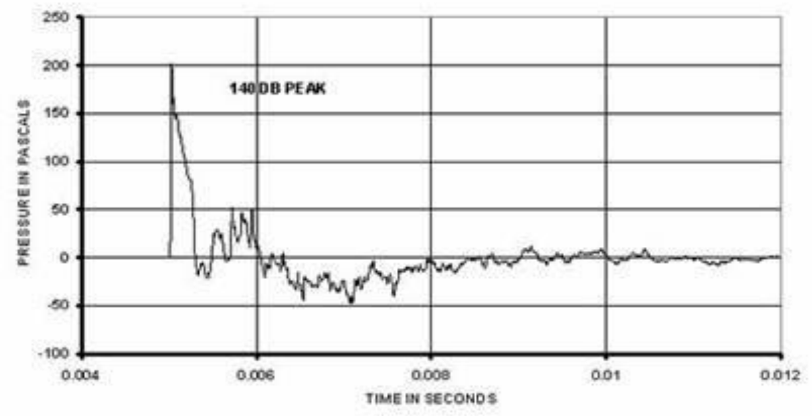

Figure 1. Pressure history of M-16 rifle at 90 degrees to line of fire at a 140 dB peak pressure level.

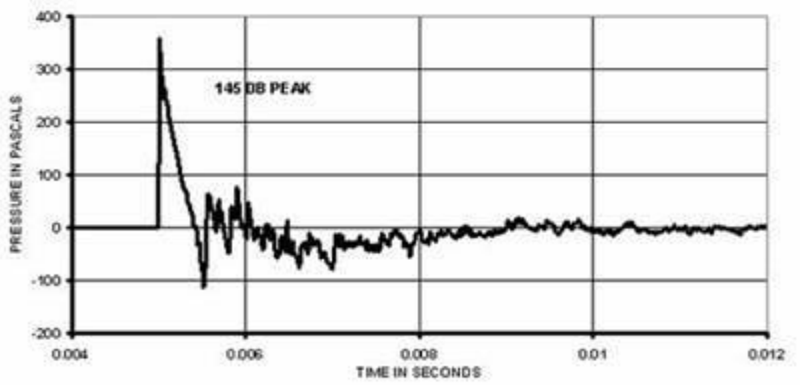

Figure 2. Pressure history of M-16 rifle at 90 degrees to line of fire at a 145 dB peak pressure level

2. Higher level impulses at the firer's ear

Two exposures were conducted at the firer's ear location where the waveform is relatively complex. In one case, the weapon was fired with the standard muzzle device and in the second, an experimental device was substituted. The impulse with the standard muzzle device is presented in Figure 3. The peak pressure is 157 dB and the A-weighted energy is about 1.0 J/m2. The substitute muzzle device was in reality a small muzzle brake that had been produced as part of other tests. Its effect was interesting because it produced a very high peak pressure in the firer's ear location (peak pressure of 169 to170 dB); with an A-weighted energy of 9.0 J/m2, shown in Figure 4, all the while maintaining essentially the same spectrum, seen in Figure 5. The difference between these two pressure histories is more apparent when they are put on the same intensity scale as in Figure 6. This particular combination of impulses is particularly interesting from a theoretical standpoint. The impulse produced with the experimental muzzle device is, by normal methods of reckoning, clearly the more hazardous. The nine-fold increase in energy, the 12-dB higher peak pressure and the same spectrum, would all seem to argue for the greater hazard. In looking at Fig. 6 it is difficult to see how the larger impulse could fail to be more hazardous. On the other hand, the AHAA model predicted that because the middle ear had become highly non-linear at the higher pressure, the resulting hazard at the level of the cochlea would be about the same for the two impulses. It also predicted that one impulse of either type would produce a large threshold shift. Thus, this exposure constituted a critical test of the proposed non-linearity in the cochlear input, as well as providing a more complex impulse.

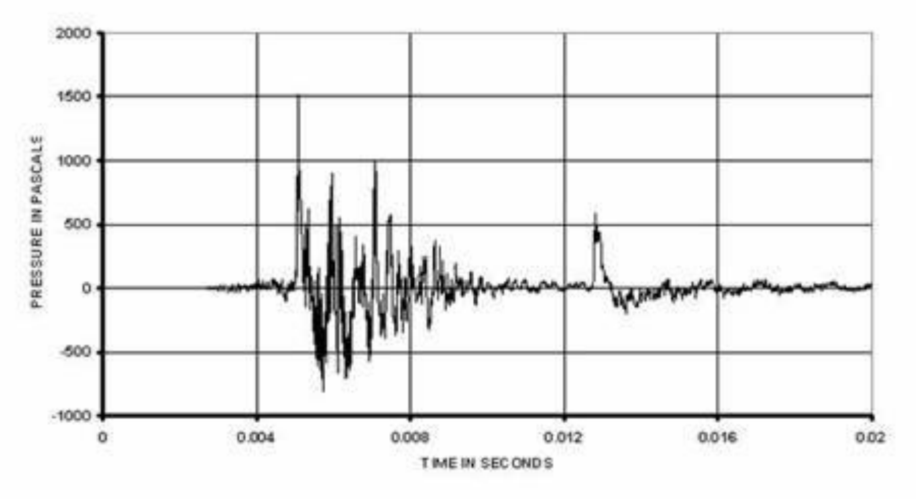

Figure 3. Pressure history of M-16 with normal muzzle device at the location of the firer's ear

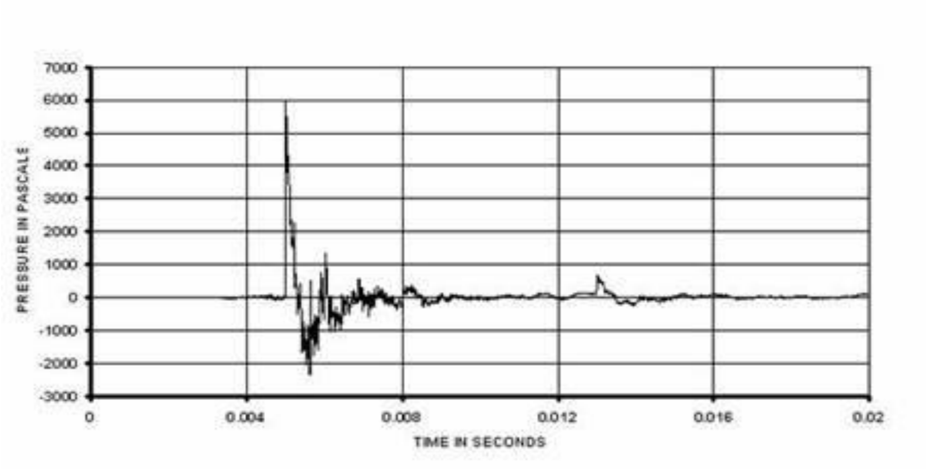

Figure 4. Pressure history at the firer's ear with an M-16 rifle fitted with the experimental muzzle device.

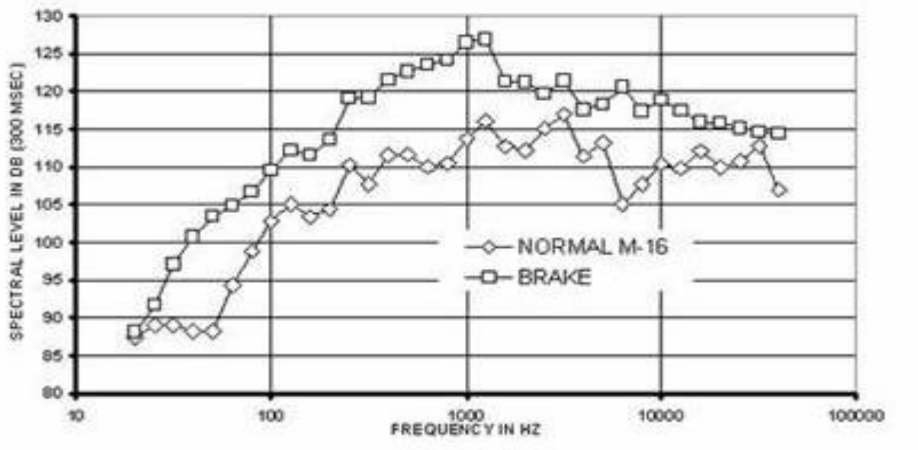

Figure 5. Spectra of the impulses in Figures 3 and 4. (The ordinate represents the energy level present in 300 msec (the complete impulse is included.)

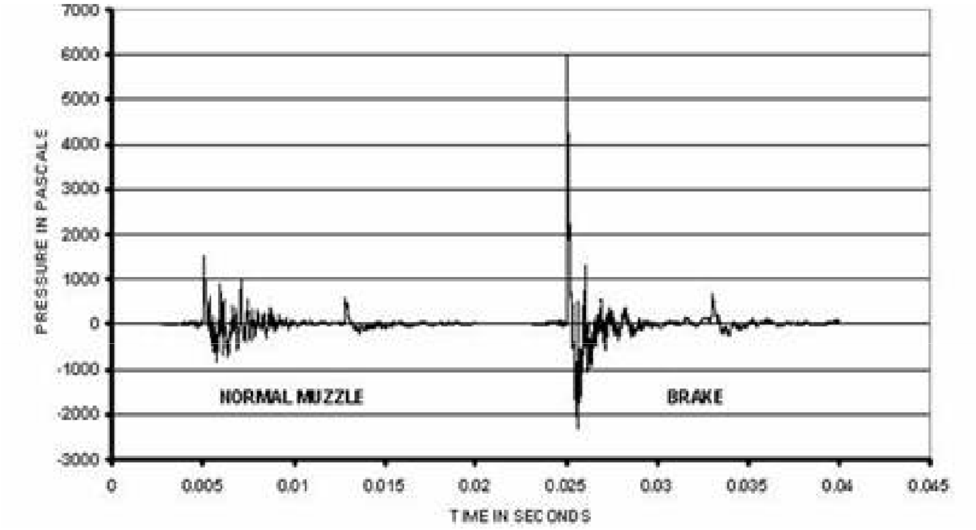

Figure 6. Pressure histories of M-16 impulses at the firer's ear on the same ordinate.

3. Complex impulses at a modest level

The final two cases reported here were chosen because they also provided a more complex pressure history and because they would allow an intermediate number of impulses to be tested (the other ten cases tested had all been 1- or 50- impulse exposures). At 4 m to the left rear of the weapon with its normal muzzle device, on an azimuth of 200 degrees from the line of fire, the waveform has a peak pressure of 144 dB and an A-weighted energy of 0.04 J/m2, shown in Figure 7. Compared to the impulse recorded at 90 degrees to the line of fire (Figsures 1 and 2), the initial portion of the waveform (the "traditional weapons impulse") is less prominent and the latter portion is much more prominent. For the traditional impulse, about 90% of the energy is in the initial portion of the waveform, whereas in the impulses recorded at the firer's ear or at the present location, only about 40% of the energy is in the initial impulse. For the impulse in Figure 7, the AHAA model predicted that 6- and 12-impulse exposures would produce appreciable threshold shifts.

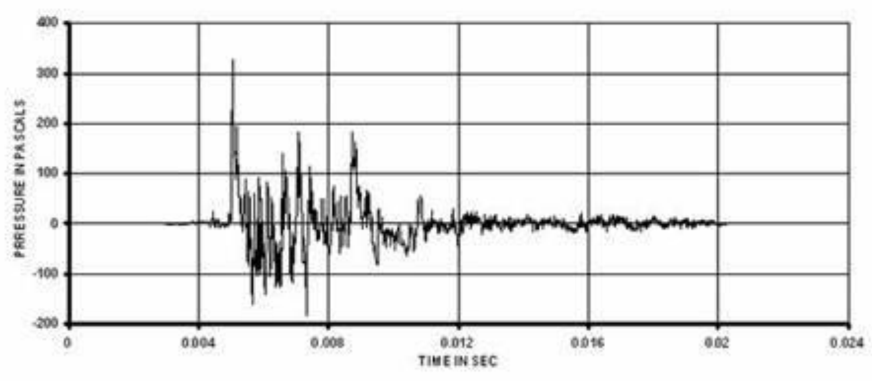

Figure 7. Pressure history of M-16 rifle at 4 m on an azimuth of 200 degrees (left rear).

III. PROCEDURES

A. Recording conditions

Waveforms were detected by a Bruel & Kjaer (B&K) ¼", Model 4166 microphone oriented at grazing incidence to the wave front. They were digitized with 12-bit A to D converters operating at 100 kHz and stored on a disc. The system was calibrated with a pistonphone (B&K Type 4220) before each recording session. Waveforms were also recorded during all exposures with the microphone situated at grazing incidence between the two animals being exposed and at the line of their ears. **B. Exposure conditions.**

The exposures were conducted out of doors in calm wind conditions (velocity less than 16 km/hr). The rifle was supported on a stand with the muzzle 1.7 m above the ground and was remotely fired into a distant bullet trap. There were no reflecting surfaces near the animals (other than the ground) that produced appreciable energy. In all cases, the animals, exposed in pairs, were anesthetized at the time of the exposure and had to be supported at muzzle height on a metal plate the size of their body and with a small chin rest keeping their heads up and pointed toward the impulse source. During the exposure, the animals' body temperature was maintained with a hot-water heating pad.

C. Audiometric assessment

The method of audiometric assessment was essentially the same as in the studies reported earlier (Price & Kalb, 1999; and Price & Wansack, 1989). In essence, experimental animals were anesthetized with sodium pentobarbital and their body temperature was maintained with a hot-water heating pad and controller. Brain stem potentials were recorded from the vertex in response to 2-, 4-, 8 -, and 16-kHz tone pips (3 cycles on rise, plateau, and fall). For four of the six exposures thresholds were also tested at 1 kHz as well. Pips were presented through an Etymotic earphone in the ear canal. Thresholds were sought in 5-dB steps and were taken to be half way between the lowest intensity at which wave V was discernible and the next lower step. Typically, 1024 pips, delivered at 10 per second, were averaged for analysis.

Losses were taken to be the difference between the pre-exposure measure and the post-exposure measure. In the event that no threshold was measurable at the highest intensity the system could produce (about 90 dB), the loss was arbitrarily taken to be 80 dB.

D. Testing procedure

Experimental groups consisted of 10 animals. Animals first had their hearing sensitivity tested in both ears; they were then exposed to the noise and again had their hearing tested. The second test was begun about ½ hour after the exposure.

Given that threshold shift following these very intense exposures does not tend to recover over a period of several hours and may even grow a little larger in that time (Hamernik, Ahroon, & Patterson, 1988), no adjustment was made in the data to account for the exact time that the threshold measurement was made. A recovery period of 2 months followed, at which time, a final test was done on both ears.

IV. RESULTS AND DISCUSSION

In analyzing the loss data with the AHAA model we have chosen to use the losses at the frequency showing maximum loss for the group of ears. This is either 2 or 4 kHz in all cases. This procedure is consistent with the application of the AHAA model, which predicts the maximum loss. Clearly, the mid-range of frequencies is most susceptible, probably because that is where the ear conducts energy the best. **A. Initial sensitivity.**

The six groups were all very close in sensitivity; consequently, the mean sensitivity for the 120 ears is reported in Figure 8. The standard deviations average about 5 dB, typical of good clinical audiometry on normal ears.

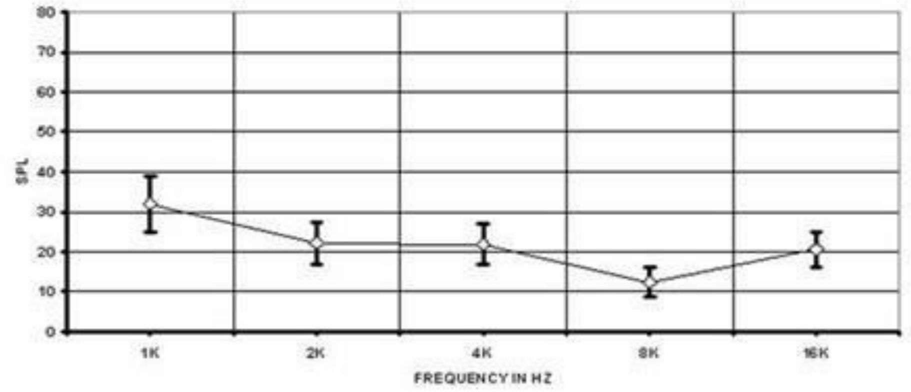

Fig. 8. Mean initial sensitivity of all the ears tested (N=120). (The bars are one standard deviation.)

B. Loss to the rifle at 140 and 145 dB peak, 90-degree azimuth

Losses measured immediately are labeled compound threshold shift (CTS) reflecting the fact that they contain both temporary and permanent components. CTS and permanent threshold shifts (PTS) for the 50 impulse, 140 dB exposure, are presented in Figure 9 and the parallel data for the 145-dB peak pressure exposure are presented in Figure 10. Losses for the 145-dB peak exposure were greater than for the 140-dB exposure, as one would expect.

However, it was surprising to see that the frequency showing greatest loss was 2.0 kHz for the 140-dB exposure, because the greater loss is typically at 4.0 kHz, as it was for the 145 dB exposure. The difference between the loss at 2.0 and 4.0 kHz is statistically significant (P= 0.02, single tailed T-test, 18 DF, homoscedastic variance). In the case of the 145-dB exposure the loss at 4.0 kHz was greater than the loss at 2.0 kHz, as expected, although not significantly greater (P =0.19, single tailed T-test, 18 DF, heteroscedastic variance). The reason for the difference between the 140 -and 145-dB case is an interesting speculation from a theoretical standpoint. If we try to explain the shift of maximum effect using the concept of spectrum, we fail. The magnitude spectra of the two impulses are presented in Figure 11. The two spectra are highly similar and show no obvious bias toward a lower (or higher) frequency for either impulse. If the spectrum for the 140-dB impulse is raised by 5-dB to facilitate comparison (Figure 12), it would appear that there is a slight bias of the 140 dB impulse toward energy at a little higher frequency just above 1.0 kHz. This, however, runs counter to the hearing losses that were at a higher frequency for the 145-dB exposure.

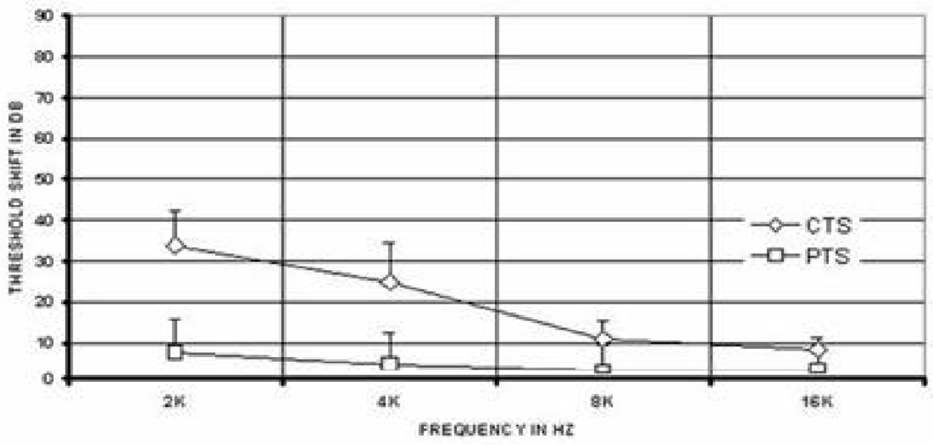

Figure 9. Mean CTS and PTS to 50 rifle impulses at 140-dB peak. (Bars equal 1 standard deviation, N=20 ears of 10 animals.)

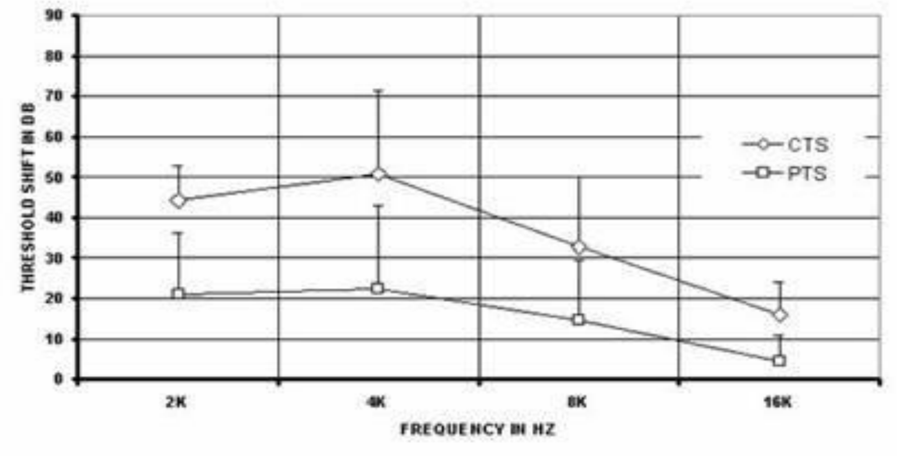

Figure 10. Mean CTS and PTS to 50 rifle impulses at 145-dB peak. (The bars equal 1 standard deviation, N=20 ears of 10 animals).

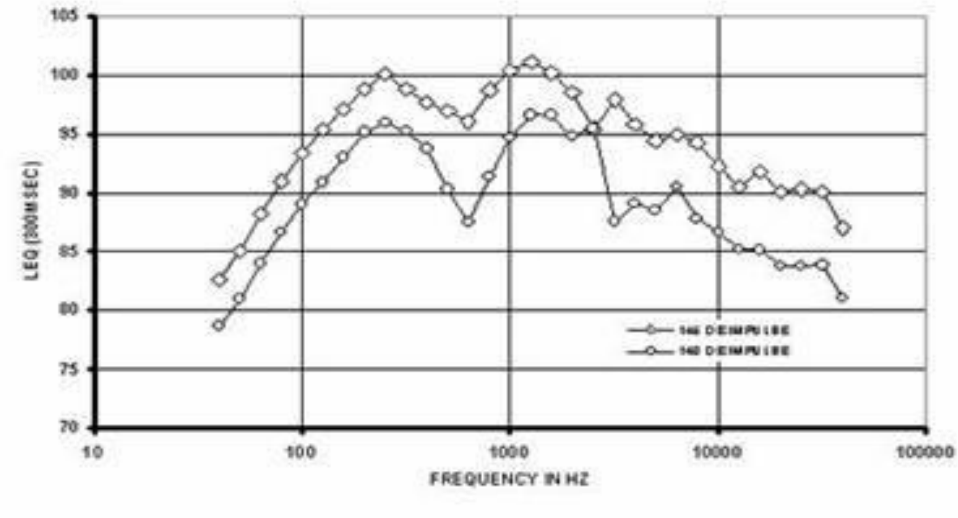

Figure 11. Magnitude spectra of the 140 -and 145-dB rifle impulses. (Values are the levels present in a 300 msec period.)

Alternatively, when the two impulses were processed with the AHAA model (described in Kalb & Price, 2003), the analysis was consistent with the data. Figure 13 depicts hazard in AHUs as a function of cochlear location. In this plot, it is apparent that the area of maximum effect within the cochlea is predicted to be more basal (toward higher frequency) for the 145-dB impulse than for the 140 dB impulse. This is the pattern of loss that was actually seen. It would be imprudent to make too much of this correspondence between the model's prediction and the threshold shift data. In the damaged ear, for example, the stiffness of the basilar membrane-Organ of Corti complex has clearly been altered; therefore, the exact location of the "place" of the audiometric stimulus is likewise uncertain. Nevertheless, it does appear that the model is sensitive to details in the pressure histories that traditional methods of analysis are not.

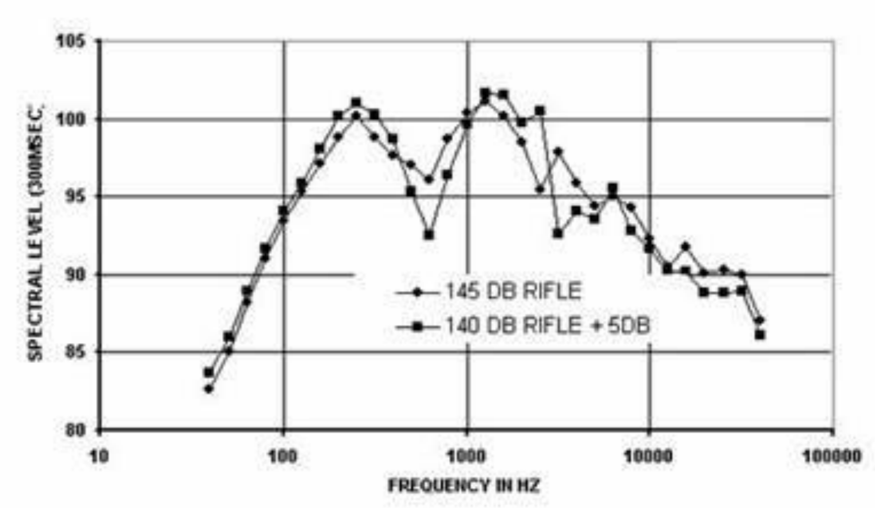

Figure 12. The same spectra as in Figure 11, except that the levels for the 140-dB impulse have been raised 5-dB to permit comparison.

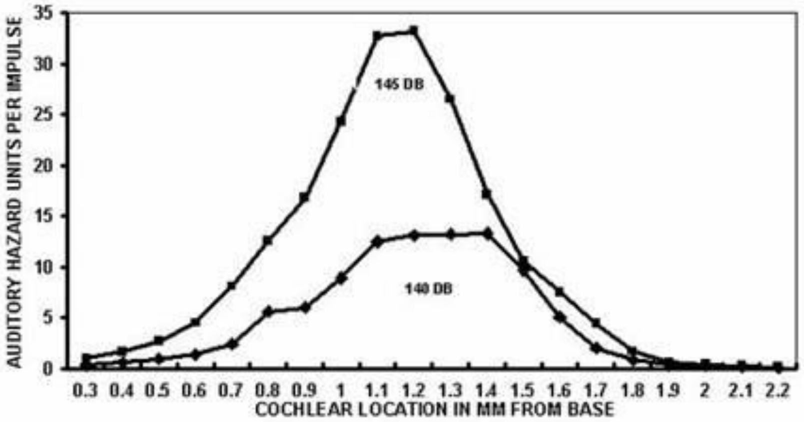

Figure 13. Hazard from the 140 -and 145-dB rifle impulses as analyzed by the AHAA model.

C. Loss to single rounds from the rifle

The losses to a single round at the firer's ear with the normal muzzle device appear in Figure14, and the losses to the same weapon with the muzzle brake are presented in Figure 15. It is perhaps surprising that the losses in the two figures are essentially the same, considering that the incident waveforms differed so much in their peak pressures (12 dB) and the A-weighted energy in them (9.0 dB). These two impulses had been selected for use in testing because the AHAA model had predicted that they would be about the same in their effects as a result of the peak-limiting effect of the stapes suspension, in spite of the great differences in peak pressure and energy in the free field. The hearing loss data are consistent with the model's prediction. If the two impulses were reduced within the computer to a very low pressure regime where the peak-limiting effect is negligible, the model predicts that the higher peak pressure impulse would generate about 12 times the "dose" of the smaller, as would be expected. The arguments for peak limiting had been developed on a largely rational basis (Price, 1974) with some empirical support showing an incipient non-linearity in Guinan and Peak's study of the cat middle ear (their Figure 6, 1967). More recently, Dancer (2000) measured intra-cochlear pressures in the guinea pig as peak pressures from impulses were delivered to the ear and also found peak limiting in the intracochlear pressure and Huttenbrink (1988) has observed the limiting process directly. The hearing loss data as well as the pressure-limiting data are all clearly supportive of a peak-limiting effect in the middle ear.

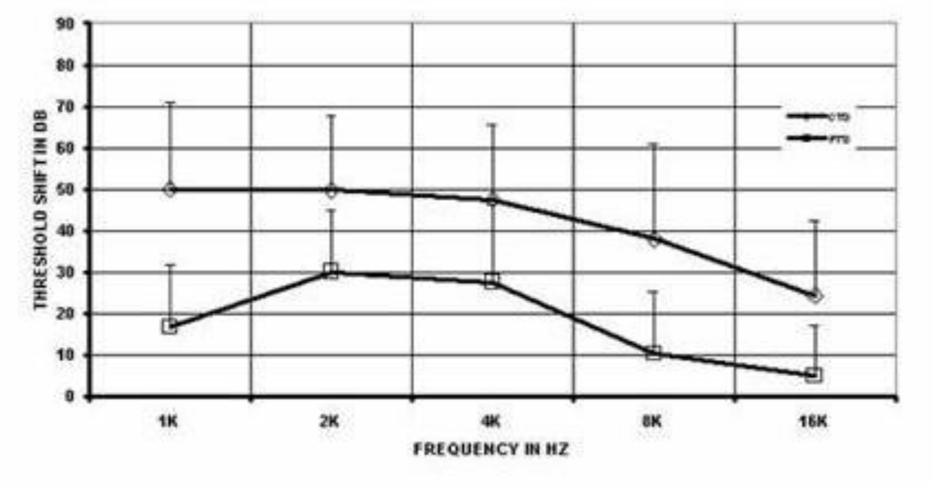

Figure 14. Mean CTSs and PTSs to a single round from the M-16 with a normal muzzle device. (Exposed at the firer's ear location. The bars indicate one standard deviation, N=20 ears of 10 animals.)

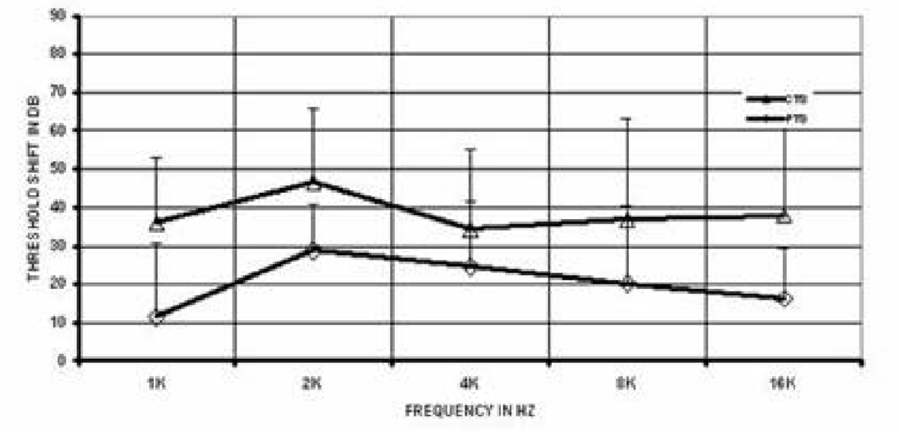

Figure. 15. Mean CTSs and PTSs to a single round from the M-16 with the experimental muzzle device. (Exposed at the firer's ear location. (The bars indicate one standard deviation, N=20 ears of 10 animals.)

D. Loss to the rifle at 144 dB peak, 200-degree azimuth, 6 and 12 round exposures

There were two exposure groups for this condition, one exposed to 6 rounds and the other to 12 rounds. The CTSs and PTSs for each exposure are presented in Figures 16 and 17. As expected, the 12-round exposure produced a little less than twice the loss of the 6-round exposure. It is possible that the CTSs for the 12-round exposure might be a little lower than they should be because in 7 ears at 1.0 kHz and 6 ears at 2.0 kHz (of the 20 ears tested) the losses were unmeasurably large and we had to assign the value of 80 dB loss, as was our convention in such cases. In any case, the amount of loss seen in both these exposures makes them suitable for evaluating the hearing loss model. Like the primer impulses, these two exposures produced large losses with relatively little energy (30 and 52 dB mean CTSs with 0.24 and 0.48 J/m2 , respectively, which are LAEQ8 levels of 69 and 72 dB). In terms of A-weighted energy, these energies in continuous noises would not be expected to produce even small losses in the cat ear, given many exposures. On the other hand, when the level is high enough (144 dB peak in this case), the damage mechanism is likely to be mechanical stress and the loss can grow very rapidly with relatively little energy.

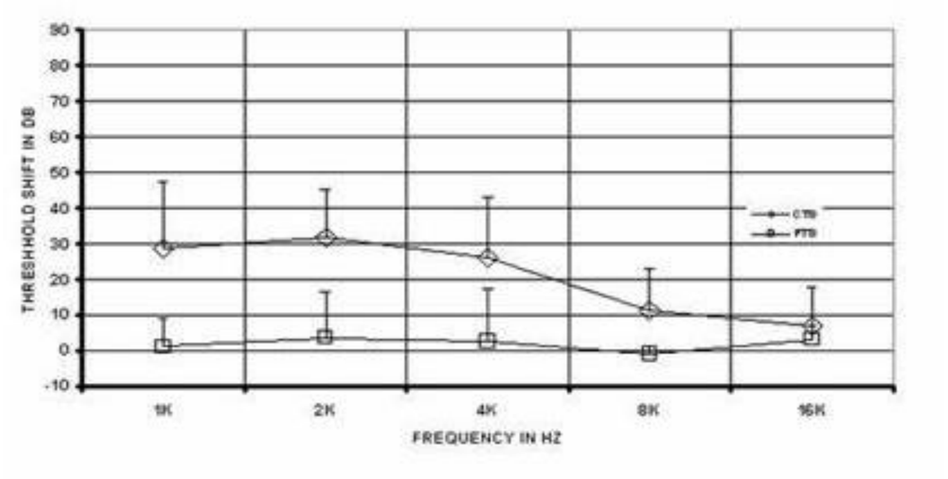

Figure 16. Mean CTS and PTS for exposure to 6 rounds from the M-16 rifle at 200 degrees azimuth, 144 db peak pressure. (The bars indicate one standard deviation, N=20 ears of 10 animals.)

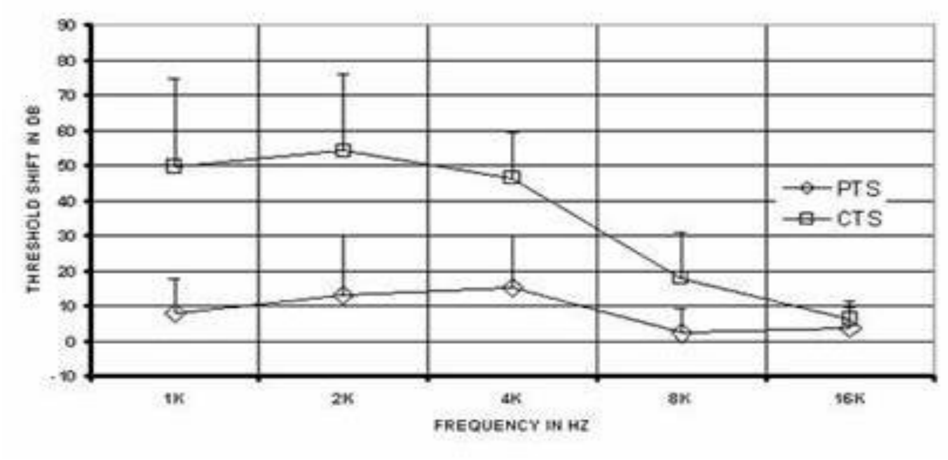

Figure 17. Mean CTS and PTS for exposure to 12 rounds from the M-16 rifle at 200 degrees azimuth, 144 db peak pressure. (The bars indicate one standard deviation, N=20 ears of 10 animals.)

V. GENERAL DISCUSSION

A. Relationship of CTS to energy in the exposure

At least as a first approximation, it would be reasonable to think that the effect of intense sounds ought to be related to the flow of energy into the cochlea (Patterson, Hamernik, Hargett, & Ahroon, 1993; Price, 1979; Price & Kalb, 1991; Rossowski, 1991). If true, then it is apparent that the acoustics of the external and middle ears play a major role in shaping that flow and a weighting function characteristic of a particular species ought to be able to reproduce the transfer function of energy in the free field to energy entering the cochlea.

A-weighting is an example of a filter performing such a function. The foregoing argument should apply so long as the external and middle ears are linear in their operation. If, however, the middle ear has a peak-clipping non-linearity at high SPLs (Price, 1974; Price & Kalb, 1991), then the analytical problem becomes much more complex and we lose the possibility of a single weighting function serving to rate hazard. A look at the data from this perspective supports this contention.

In this analysis, it will be useful to combine the data from the six exposures in studies already reported (three exposures to airbags [Price & Kalb, 1999] and three exposures to primers [Price & Wansack, 1989]) with the data presented in this paper. The data from the previous studies had been collected by essentially the same methods; therefore, they can be meaningfully compared. First consider the use of A-weighted energy as a rating method. Figure18 presents the mean CTSs for all 12 exposures as a function of the A-weighted energy in the total exposure. Overall, the CTSs show a rather poor relationship to A-weighted energy in the impulse. The individual data points represent the mean CTS (at the frequency showing maximum loss) of 10 animals (20 ears) for each of the exposures. To a first approximation it appears that 30 to 60 dB of CTS have been produced by anywhere from 0.1 to almost 100 J/m2 (a range of 30 dB in energy). It is interesting that the largest loss (72 dB) was a function of only 0.35 J/m2 in the exposure while as little as 0.05 J/m2 is near the threshold for a PTS (data point showing 8 dB of CTS) (Price & Wansack, 1989). Put in terms of an 8-hour LAEQ, the onset of PTS from a single exposure would be less than 65 dB (at least for these impulses)! Without middle ear muscle protection and with an impulse putting its energy where the ear is tuned, it appears that the cat ear is exquisitely sensitive to loss.

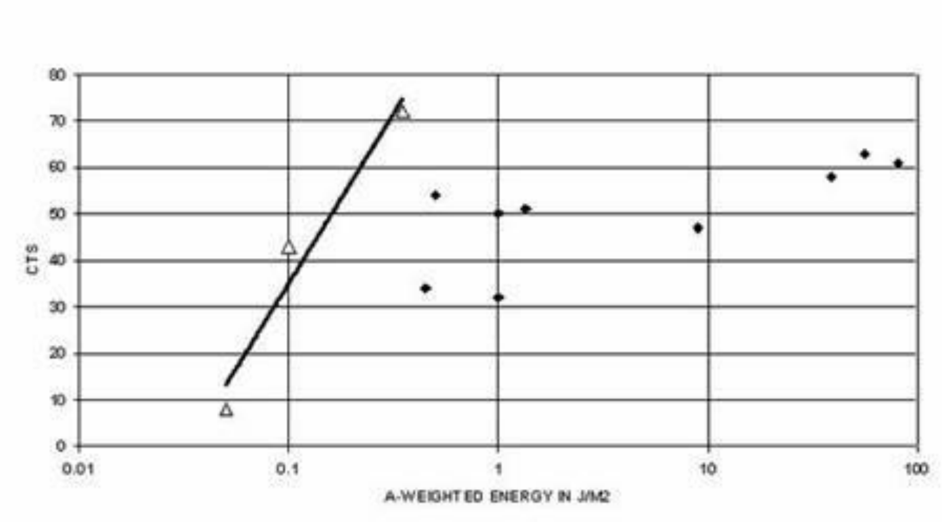

Figure 18. Mean CTSs for 12 experiments with the cat ear (see text) exposed to impulsive sounds as a function of the A-weighted energy in the exposure. Each data point represents the mean loss at the frequency showing greatest loss for both ears of 10 cats. The trend line fits the exposures with the primer (triangular data points).

It might be argued that A-weighting is just not the right weighting function for rating impulse noise hazard for the cat ear. In fact, the same argument has been made for A-weighting, impulse noise and the human ear (Buck, Dancer, & Parmentier, 2000; Chan, Ho, Kan, Stuhmiller & Mayorga, 2001). But seeking the 'right' weighting function would appear to be a fruitless approach. From a theoretical standpoint, if we believe that the ear has a peak-clipping non-linearity built into the conductive mechanism, then it is irrational to seek a single weighting function that will work for all intensities for a wide range of stimuli.

Another viewpoint regarding energy as a metric is illustrated by the line of best fit for the three left-most data points in Figure 8. These data came from the 3 exposures to 50 impulses from a primer at 135-, 140- and 145-dB peak pressure levels (Price & Wansack, 1989). In these exposures, the only thing that changed was the peak pressure in the impulse. Analysis with the AHAA model predicted that the middle ear was essentially linear (within 1 dB over the 10 dB range), which is consistent with the Guinan and Peake (1967) analysis of the cat middle ear. The slope of the line indicates that loss grows very rapidly, once some level is exceeded (about 7 dB of CTS for every decibel of increase in peak pressure above ~135 dB). Yet the CTSs for the other nine exposures obviously do not fall along this line. A-weighting might work for a highly restricted data set; but it is too simplistic for a wide range of intense stimuli.

B. An ear model as an alternate method of analysis

Given the complexity of the ear's response, the need for a computational procedure that captures the conductive path to the cochlea as well as an algorithm that predicts hazard at various locations in the cochlea is apparent. Indeed, if the AHAA model of the cat ear is used to process these data (Kalb & Price, 2003; Price & Kalb; 1998; 1996a, 1996b; 1991), a different picture emerges2. In the model, which is an electroacoustic analog of the ear, hazard is taken to be the result of upward displacements of the basilar membrane. The output from the model is in AHUs. The same 12 exposures appearing in Figure18 are re-plotted against AHUs rather than energy in Figure 19. In this case, the fit to the data is much better than it is to energy in the free field, the line of best fit showing a correlation of 0.94 between the data sets, a remarkably good fit.

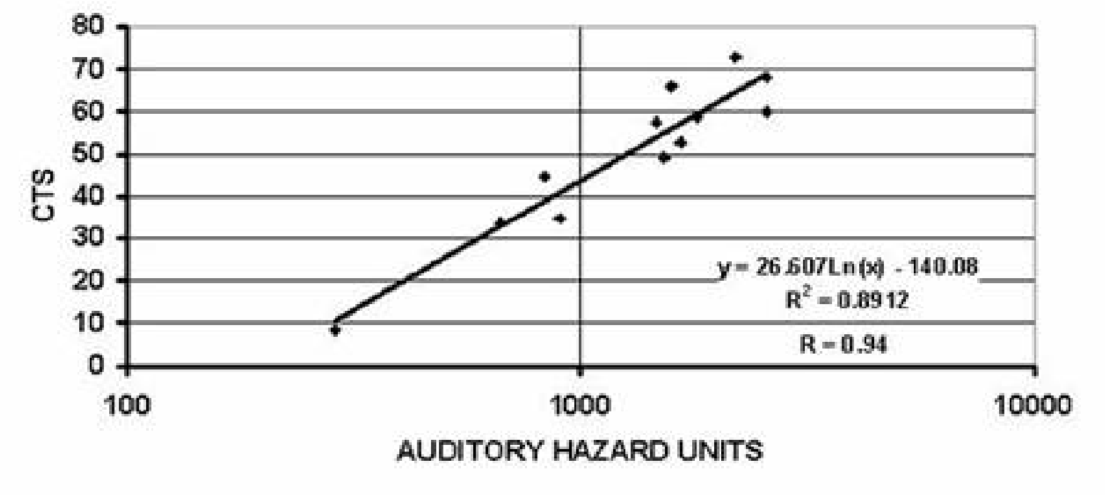

Figure 19. CTS for 12 experiments with the cat ear (see text) exposed to impulsive sounds as a function of the AHUs calculated with the AHAA model of the cat ear. (Each data point represents the mean loss at the frequency showing greatest loss for both ears of 10 cats. The trend line represents the least squares fit to all the data.)

The question naturally arises as to why the model fits the data so well when a weighted energy measure does not. First, the model does "weight the energy" because it reproduces the ear's transfer function for energy from the free field to the middle ear. Thus, the low and high frequencies are transmitted less well than the mid-range, much as the A-weighting function does. The factor making the major difference is the stapes that becomes non-linear when displacements rise above 5 or 10 microns and peak limits at about 20 microns. The presence of such a non-linearity explains why the ear can tolerate very high energies for some exposures and very little energy for others, even when A-weighted. For example, data from the human ear show that 3000 J/m2 is tolerable for cannon-like impulses (under a muff) (Patterson, Mozo, Gordon, Canales, &Johnson, 1997) and less than 10 J/m2 is unsafe for rifle impulses (Brinkmann, 2000; Price, 2003).

We conclude that the fit of the model to these data is about as good as can be obtained, which means that the model could be transformed into a human version by the use of anatomical values appropriate to the human ear. Once the fit matched the transfer functions for the human ear, it could then be tested against the human hearing loss data. If necessary, the human version could be adjusted to match the human data set.

FOOTNOTES

[1] In this paper, A-weighted energy has been used as a reference measure. Strictly speaking, A-weighting energy is a procedure that has aspecifically defined meaning for the human ear. The A-weighting function mimics the frequency-related sensitivity of the human ear at 40 dB (SL), primarily by reducing the contributions of the low frequencies. The shape of the auditory sensitivity curve for the cat and human are similar (Miller, Watson & Covell, 1963), so the A-weighting function serves approximately the same function for the cat ear as well.

[2] In obtaining the data in Figure 18, certain of the variables in the model were adjusted to produce the best fit. The purpose of these 12 experiments with the cat ear was to provide hearing loss data that would allow adjustment of the model to reflect reality. The model is a formal electro-acoustic analog of the ear, which means that one is largely constrained to adjust variables only in ways that are consistent with anatomy or properties of materials. On the other hand, the model included certain variables that could only be estimated. For example, the algorithm that calculates hazard at the level of the basilar membrane (BM) takes the peak upward flexes of the BM, in microns, and raises them by a power and accumulates the value (AHUs) at that location. There was an expectation (from studies of the fatigue of materials) that it should be near 2 (Broch, 1979), but there were no real guidelines. Or the model included a term ("Ramp" for Resistance amplification) that was intended to represent certain properties of the ossicular chain, namely processes that would act to dissipate energy though motions not along the normal conductive path. The middle ear is suspended on ligaments that simply must allow the middle to move in non-traditional ways at very high sound pressure levels, such as the rocking stapes movement observed by von Bekesy (1949). That such dissipative movements exist seems certain, but the value of "Ramp" simply had to be estimated and adjusted to fit the hearing loss data.

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Note

In conducting the research described in the report, the investigators adhered to the Guide for the Care and Use of Laboratory Animals, as promulgated by the National Research Council, National Academy of Sciences Press, Washington, D.C. 1996.

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