Hearing protectors and hazard from impulse noise: melding method and models

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Abstract: Studies agree that the protected ear tolerates surprising amounts of energy at very high levels; but with no theory to explain these results, practical application of such findings is like traversing an acoustic minefield. Our modeling of auditory hazard [G. R. Price and J. T. Kalb, J. Acoust. Soc. Am., 100, 2674 (1996)] suggests the physical basis for the ear’s resilience is a function of interaction between the hearing protector’s effect on the waveform arriving at the ear and the ear’s own complex responses to intense stimulation. We believe that the primary physical basis for hazard is mechanical stress at the level of the hair cell; hence assessment needs to take place in the time domain. Calculation begins either with the pressure history measured under a hearing protector or one derived from a free-field pressure and attenuation measures on the protector. The ear model includes an active middle ear muscle system, an amplitude-limited stapes displacement and an algorithm for calculating hazard in the cochlea which integrates peak upward stresses at the level of the basilar membrane. In the end, the protected ear’s resilience is predictable and can be understood as part of a general theory of auditory hazard.

THE HEARING PROTECTOR PARADOX

Data from experiments using intense impulse noise exposures have challenged our understanding of how intense sounds affect the ear. They have established that the human ear, under circumaural hearing protectors providing only modest attenuation, can tolerate immense amounts of energy (>500,000 j/m^2) in a single 100 impulse exposure. The exposed ears show virtually no effect in even the 95th percentile subject. It would appear that the ear muff had done an extraordinary job of attenuating the sound and protecting the ear. However, pressures measured under the protector indicated nothing remarkable in the protector’s performance as an attenuator. Pressures under the muff had peaks well over 170 dB and A-weighted energies in the exposures were over 2000 j/m^2. This energy is equivalent to almost one work-year at 85 dBA; hence the lack of effect for such a large exposure is still surprising. Furthermore, current noise standards for impulse noise agree in predicting that such exposures should produce threshold shifts well in excess of that which is allowable. The U.S. criterion would allow less than one impulse and the French criterion for impulse noise exposure, which is based on A-weighted energy, would allow just one impulse. If one rigidly held to the proposition that A-weighted energy is the appropriate index of hazard for intense impulses, then these results also fly in the face of common practice which suggests that virtually all exposure to small arms impulses should be with hearing protection. Yet, an acceptable exposure of 2000 j/m^2 would allow about 2000 impulses! Such contradictory findings are disconcerting to the orderly mind. However, we believe that if theory is coupled with hypotheses, then reason need not be abandoned and a semblance of order can be established.

THE PROBLEM ANALYZED

We believe that attention should not be focused on the hearing protectors themselves. Pressures were measured under the muffs in the noise exposure experiments and the data were essentially unremarkable. A study of hearing protector performance in impulse noise (the IMPRO study), recently conducted in Europe, similarly found no major surprises with respect to the physical measures of hearing protector attenuation. The problem that remained even after the IMPRO study was that no one was sure what to do with the waveforms measured under the protectors in order to predict their effectiveness in reducing hazard. All the impulse noise standards have been based primarily on data from unprotected ears exposed in the free field, a very different environment than a sound field under a muff or plug. There were no obvious additional avenues to pursue in the area of physical measurements.

We believe that the proper focus for an explanation lies in the ear and its responses to intense sounds. In an attempt to deal with the problem of intense noise we have devised a mathematical model of the ear which predicts hazard to the ear by calculating energy transmission from the free field through the ear to the level of basilar membrane displacements and summing the upward displacements there into an estimate of hazard. This model, developed first for the cat ear, has been validated with biological ears exposed to a wide range of impulses. The
correlation coefficient for the relationship between calculated hazard and actual hearing loss is better than 0.9 for mean data for groups of ears. This high degree of correspondence between the predicted and actual hearing losses suggests that the model is essentially on the right track. Furthermore, because it is formulated in a manner conformal with the ear's structure, it allows hearing protection to be included in the analytical path and provides critical insights into the present problem.

We have exercised the model with a variety of intense impulses and we find that four things act to explain the ear's surprising tolerance to intense sound. First, the conductive path into the ear is tuned to permit energy flow in the mid-range and to cut it off above and below that point. This is the physical basis for the success of the A-weighting function. Secondly, the annular ligament of the stapes acts to limit displacement, thereby modulating cochlear input. The stapes can displace only a few tens of microns, yet intense impulses would try to drive it many hundreds of microns. Hence energy flow into the cochlea is dramatically limited at very high sound pressures. Thirdly, we believe that the middle ear muscles were active during the noise exposures and were able to contract in advance of the impulses, providing critical additional attenuation of the impulse. Contractions were able to occur in advance of the impulses both because of an audible countdown, and because the subjects were practiced. And lastly, the model allowed the pressure measured under the muff to enter the calculational process at the ear canal entrance (as it should). This avoided "double counting" energy in the mid-range (as when A-weighting is used to evaluate a pressure measured under a muff). If all these elements are included, then the model predicts that the exposures were indeed in the tolerable range for the human ear. As the full complexity of the ear's response to intense sounds is appreciated, the hearing protector paradox is resolved.

REFERENCES