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Hazardous Exposure to Impulse Noise

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Hazardous Exposure to Impulse Noise

SEL may be the best Criterion for Quantifying Impulse

Working Group on Hazardous Exposure to Impulse Noise

LUZ says "No". Response is too non-linear for SEL to work.

Committee on Hearing, Bioacoustics, and Biomechanics

Commission on Behavioral and Social Sciences and Education

National Research Council

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Hazardous Exposure to Impulse Noise

INTRODUCTION

Limits for exposure to hazardous agents are set by defining some specific acceptable effect (the response) and then determining what exposure conditions (the dose) produce that effect. In 1968, the Committee on Hearing, Bioacoustics, and Biomechanics (CHABA) proposed a limit for exposure to impulse noise (gunfire) in which the response was a specific amount of temporary threshold shift (TTS) and dose was specified in terms of the peak pressure and two aspects of the duration of a particular impulse, with correction factors for number of impulses and for the angle of incidence on the ear. The proposal was basically an endorsement of one advanced by an Anglo-American team of investigators (Coles, Garinther, Hodge, and Rice, 1968) that was based on the very limited pool of information then available about the auditory hazard of gunfire. Coles, Garinther, and Hodge were members of the Working Group on Proposed Damage-Risk Criterion for Impulse Noise (Gunfire).

The 1968 criterion was essentially developed from experimental data obtained from studies using impulses produced by gunfire. It was not intended, as the discussion by Coles et al. (1968) makes clear, to be used for industrial types of impulses (impacts). This discussion of the 1968 document is thus limited to impulses produced by gunfire. The proposed guidelines were highly tentative, involving extrapolation from very limited actual data on the temporary effect of only small arms gunfire on hearing; it was recognized that modification of the specific numerical values of the permissible exposure descriptors could be expected as more data became available. In fact, it was considered possible that the descriptors used would be found to be inappropriate, and that exposures might better be characterized in terms of the rise time, spectral characteristics, and total acoustic energy of the impulses. Furthermore, the 1968 proposal made no provision for the assessment of the hazard of exposure to a series of different impulses of different peak sound pressure levels (SPLs) with various interstimulus intervals or of impulses in combination with other forms of noise (steady, intermittent, or impact noises), nor was consideration given to the effects of hearing protector use.

The proposal of the 1968 CHABA working group was never adopted in its entirety by any regulatory agency, although some of its provisions were incorporated into military standards. In the ensuing decades, numerous alternative methods for evaluating exposure have been suggested, but widespread agreement on a preferred procedure has not been reached. It was therefore deemed worthwhile to review the 1968 proposal in order to determine whether changes should be made. Accordingly, in 1988 CHABA established a working group "to review, analyze, and synthesize the literature (since 1968) on hazardous exposure to impulse noise. The working group will recommend research for revision of the 1968 criterion."

THE 1968 PROPOSED CRITERION

(1) *The Response.* The criterion response proposed by the Working Group on Proposed Damage-Risk Criterion (DRC) for Impulse Noise was simple: generation of a TTS_2 (temporary threshold shift of auditory threshold measured 2 minutes after termination of exposure) of 10 dB at 1,000 Hz and below, 15 dB at 2,000 Hz, or 20 dB at 3,000 Hz and above.

(2) *The Dose.* An impulse was described in terms of three of its many possible parameters: (1) the peak pressure level P: "the highest instantaneous pressure level reached at any time by the impulse, expressed in decibels re 0.0002 dyn/cm^2, measured at the position of the ear with the individual not present"; (2) A-duration: "the time required for the initial or principal wave to reach the peak pressure level and return momentarily to zero"; and (3) B-duration: "the total time that the envelope of the pressure fluctuations (positive and negative) is within 20 dB of the peak pressure level, including reflected waves."

(3) *The Exposure Limits.* The basic dose-response relation of the 1968 criterion is expressed in the form of the graph displayed in Figure 1. This figure shows the permissible value of P, as a function of A- or B-duration, "for 100 impulses distributed over a period of four minutes to several hours

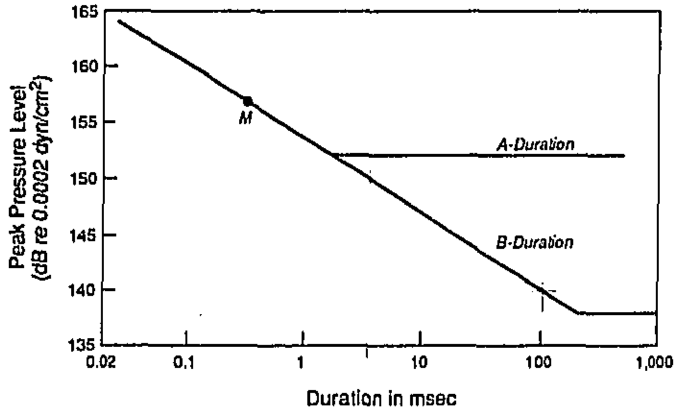

FIGURE 1 The 1968 Impulse Noise Criterion

on any single day" and reaching the ear at normal incidence. Under these exposure conditions, the criterion TTS_2 will not be exceeded in more than 5 percent of the ears exposed. If the impulses arrived at the ear with grazing incidence, the permissible peak level could be raised by 5 dB. Finally, if the number of impulses N was not 100, then the permissible peak level could be altered by 5 $\log_{10}(100/N)$ dB up or down as appropriate. Thus for example, the point M on Figure 1 indicates that, for a pulse having a duration of 0.3 msec (or 300 µsec), a peak level of 157 dB would be permitted for a series of 100 impulses arriving at the ear at normal incidence. If only a single pulse were involved, the permitted peak level would be 167 dB, and if that impulse arrived at the ear with grazing incidence, it could have a peak level of 172 dB.

It is important to emphasize what may be an obvious shortcoming in the basic relation: the graph of Figure 1 shows permissible peak pressure "as a function of A- *or* B-duration." That is, the relative hazard of an impulse is to be assessed in terms of either its A-duration or its B-duration, whichever is larger. The 1968 report states specifically: "In case of doubt as to which waveform analysis to apply, the more conservative B-duration should be used." Since in nearly every case imaginable, B-duration will be longer than A-duration, the net effect is that A-duration will not be relevant. The two durations, it should be noted, reflect relatively independent aspects of the pressure-time signature of a given impulse event. The A-duration is linked to the energy of the source while the B-duration is a function of the individual weapon and the exposure surroundings and is related to the additional energy in the stimulus arriving at the subject produced, for example, by reflections.

The 1968 proposal, then, in effect prescribed limits for exposure to gunfire that depended only on peak level, B-duration, number of identical pulses, and the orientation of the ear relative to the source. Because of severe limitations in available data as well as instrumentation technology, characteristics of the impulse, such as rise time, energy, or spectrum, could not be incorporated into the DRC. In fact, one might argue that the criterion presented in terms of A-durations and B-durations is an artifact of the then-current instrumentation limitations. Coles et al. (1968) wrote that "the spectrum is believed to be important and, while a Fourier analysis can give information regarding the spectral distribution of certain impulse waveforms, in general the spectrum is difficult and time-consuming to analyze. For this reason, this parameter has not been included in the DRC." No method of treatment of exposures involving a mixture of levels was suggested, nor was any mention made of the change in exposure limits associated with the use of hearing protectors. These and other deficiencies in the DRC were acknowledged by its authors.

With the elimination of A-duration, the 1968 limit can be reduced to a single equation defining the permitted peak level P of N impulses whose duration is B msec at normal incidence:

$$P = 138 + 6.67 \log_{10}(200/B) + 5 \log_{10}(100/N)$$

where if B > 200 msec, use B = 200 msec.

EVIDENCE SINCE 1968 RELATIVE TO VALIDITY OF THE PROPOSED CRITERION

Following publication of the CHABA criterion in 1968, various U.S. agencies (e.g., the U.S. Army and the Occupational Safety and Health Administration) derived exposure regulations from the criterion and for the next 10 years very little additional research was undertaken in the United States. With the exception of a human study by Hodge and Garinther (1970) and some animal research (e.g., Henderson et al., 1974, and Hamernik et al., 1974, in the civilian sector; Price, 1974, at the U.S. Army Human Engineering Laboratory), research on impulse noise in the United States was at a virtual standstill. In 1971, the Occupational Safety and Health Act (*Federal Register*, 1971), although not necessarily addressing military requirements, decreed that "exposure to impulsive or impact noise should not exceed 140 dB peak sound pressure level" (regardless not only of duration but also of spectrum, energy, or number of impulses). This recommendation discouraged the experiments necessary to address the military problems of high peak level impulse noise exposure, even though it did not interdict them (the regulation, it will be noted, uses the term *should* rather than *shall*). As a result of this stricture in the United States against peak levels above 140 dB, only a few experiments using human subjects that might confirm or deny the fundamental validity of the 1968 proposal for all forms of gunfire have been conducted. Despite the limitations mentioned earlier, the proposed criterion may well do what it was designed to do for some limited range of impulse parameters: i.e., indicate those exposures to actual small arms gunfire that would just produce the criterion TTS_2 in 5 percent of humans exposed.

Hodge and Garinther (1970) showed that small shoulder-fired rockets whose B-duration was 20 msec produced the criterion TTS_2 in 4-7 percent of their Army personnel exposed to a single pulse at a peak level of 160 dB, just as permitted by the proposed limit (145 dB from Figure 1, with a 10-dB increase for $N = 1$ and a 5-dB increase for grazing incidence).

A second study providing relevant information is one portion of an extensive study of impulse noise using humans conducted by Ertel in 1973 in East Germany. Twenty-six subjects were exposed in an anechoic chamber to a single shot of a 7.6 mm machine pistol having a peak level of 160 dB (normal incidence); one listener showed the criterion TTS_2 after exposure, indicating that this was indeed the limiting exposure. The proposed criterion indicates that such a single 160-dB pulse should produce the criterion TTS_2 if its duration were 3 msec. In this case, the B-duration was about 2.5 msec, thus apparently verifying the accuracy of the proposal.

Both of these results support the proposal limits, provided that only B-duration is considered—but only in that case. Hodge and Garinther (1970) avoided any mention of the A-duration of their rocket impulses, but Ertel's impulse had an A-duration of 0.3 msec. If the "use only B-duration rule" had been ignored in the latter case, the predicted tolerable peak level of a single impulse with an A-duration of 0.3 msec, at normal incidence, is seen from Figure 1 to be about 167 dB, a value 7 dB higher than the actual peak level.

One possible interpretation of the foregoing results is that perhaps A-duration really is irrelevant. This possibility, however, has been dispatched by a group of experiments recently conducted in France using human subjects (Comite Bruits d'Armes, 1990). A group of 7 men exposed to 25 reports from a cannon (peak level 159 dB, A-duration 4 msec) showed no TTS, but 5 of 11 subjects exposed at the same peak level to 10 rounds of a "light gun" whose A-duration was 0.2 msec showed a TTS at 4 kHz of more than 15 dB, so the fifth percentile must have been above 20 dB. Thus not only is A-duration relevant, but also its effect is in the opposite direction to that implied by the proposed criterion's contour: shorter pulses are more hazardous than longer ones. These human data also provide an example of a controlled study in which an exposure that should have been "safe" by the proposed criterion actually produced more TTS in the fifth percentile than allowable.

These results obtained with impulses of different duration were not unexpected, because studies with experimental animals had already demonstrated that longer A-durations were less dangerous than short ones. Price (1983, 1986; Price et al., 1989a, 1989b) had shown that, in the cat, the damage from exposure at a constant peak level was least for howitzer fire (3-4 msec A-duration), more for rifle fire (0.4 msec), and even more for primers (0.07 msec). Although some of these data are confounded by an anesthesia effect (Price, 1991), the effect does not alter the basic conclusion. The same result was demonstrated in the guinea pig by Dancer et al. (1985): comparison of the effect of 11 different impulses at a constant peak level but with various A-durations indicated that the shorter the pulse, the greater the hazard, down to 0.05 msec. All of these data imply greater hazard for shorter pulses, which is contrary to what would be expected on the basis of the overall acoustic energy in the impulses.

The most reasonable explanation of the foregoing results is that the spectral distribution of the energy is crucial, since the spectrum of a simple (free field) Friedlander wave is closely linked to its A-duration. The longer the A-duration, the lower the frequency at which the spectrum will display a maximum. Ertel (1973) performed a Fourier analysis on a host of published gunfire waveforms (all of which have near-instantaneous rise times) and found that the A-duration corresponded to about one-sixth of the period of the frequency of maximum energy, a figure in agreement with the analytical prediction (Hamernik and Hsueh, 1991). If, therefore, the hazard associated with the spectral distribution of the energy increases with frequency up to around 2,000 Hz, as implied by the transfer function of the outer ear, this hazard should increase as A-duration becomes progressively shorter, until it reaches a maximum for an A-duration of one-sixth of 0.5 msec, or around 85 µsec. For even shorter A-durations, the hazard should finally decrease, as the corresponding frequency becomes higher and higher, and the total acoustic energy in the impulse becomes the determining factor. Such a reduction in hazard for A-durations below 100 msec had already been demonstrated by Loeb and Fletcher (1968), who showed that the TTS caused by a spark discharge increased steadily in humans as pulse duration increased from 32 to 96 µsec. For constant hazard, then, a limit relating maximum peak level to A-duration should decrease, as A-duration increases, to only around 100 µsec; from that point on, the permitted peak level should increase rather than remaining constant as the proposed criterion's A-duration curve does.

Additional evidence clearly illustrating the need to consider the spectrum of the impulse can be found in Johnson and Patterson (1992). The impulse under consideration had a peak SPL between 180 and 190 dB in the free field. However, under the hearing protectors worn by the subjects, the high frequencies are filtered out, leaving a very low-frequency pulse (A-duration ≈ 7 msec.) of more than 180 dB peak SPL entering the ear. The subjects showed levels of TTS within the proposed limits. Clearly this is a result not in agreement with the proposed criterion, which overestimates the hazard when very low-frequency transients are encountered and can lead to unwarranted conclusions concerning the inadequacy of hearing-protective devices (Pekkarinen et al., 1992). One conclusion concerning low-frequency energy content impulses that can be drawn from recent chinchilla data (Hamernik et al., 1991) is that the energy in a particular frequency band transported by an impulse whose spectral peak is at the very low end of the spectrum is less effective in producing trauma than is the same amount of energy in the same octave band transported by an impulse whose spectrum peaks at a higher frequency.

The 1968 proposed criterion has limited support from two recent field studies. Jiminez et al. (1989) studied 60 normal-hearing Army recruits who fired a weapon with a peak level of 163 dB (probably .30 caliber) 25 times in about 5 minutes, producing an average TTS of 8.5 dB immediately after exposure. No mention is made of A- or B-duration nor the standard deviation of the TTS, but if the latter were 5-6 dB, the results would be in line with the present limit. Borchgrevink et al. (1985), in a retrospective study, found permanent hearing losses to be significantly increased in Norwegian military drill squads who used blank ammunition for a year that generated a peak level 10 dB higher than the customary 160 dB. The lower-level exposures produced "rare" cases of permanent threshold shift (PTS), while the high-level exposures produced consistent high-level PTS at the high frequencies. While these results are difficult to evaluate in relation to the proposed criterion because of the complex nature of the multiple exposures, they can be interpreted to indicate a threshold for damage around 165 dB and, depending on the impulse duration chosen to represent the exposure, may be in agreement with the curve of the proposed criterion.

While neither of these last two reports can be characterized as scientifically rigorous, they do not appear to contradict the limits for humans embodied in the proposed criterion. This is in sharp contrast to results with experimental animals, not adjusted for species differences, that indicate that not only high values of TTS but also permanent damage are produced by exposures that would be permitted by the proposed limits: in the guinea pig, by a single pistol shot with a 40-msec B-duration and a peak SPL of 145 dB (Cody and Johnstone, 1980), by a single spark-gap impulse with a duration of 100 μsec and a peak SPL of 164 dB (Meyer and Biedermann, 1980), or by 500 rounds of a cap pistol with a duration of 35 μsec and a peak SPL of 153 dB (Poche, Stockwell, and Ades, 1969); in the chinchilla, by a single spark-gap impulse with an A-duration of 60 μsec and a peak SPL of 168 dB (Luz and Lipscomb, 1973) or by 50 shock-tube pulses of 1-msec A-duration at a peak SPL of 155 dB (Henderson, Hamernik, and Sitler, 1974). None of the studies just cited attempted to estimate exposure values that would produce only TTS, however, so although they indicate that humans are less susceptible to permanent damage than the laboratory rodent, the magnitude of the difference cannot be estimated. Only recently have Patterson et al. (1985) shown that the chinchilla's just-innocuous exposure (i.e., one that just fails to produce permanent hearing loss) is a single loudspeaker-generated pulse with a peak SPL of 147 dB and a B-duration of 4 msec. For a 100-pulse exposure, the peak SPL needed to be between 131 and 135 dB. Price and Wansack (1989b) reported that for the exposure of anesthetized cats to 50 impulses produced by a primer (A-duration of 85 μsec, B-duration of 400 μsec), the onset of PTS was just above 144 dB. Both of these studies used impulses that had spectral peaks to which the chinchilla and cat ears are most sensitive. The proposed limit for the pulse used by Patterson et al. is 159 dB for a single impulse or 149 dB for 100 impulses. For the primer impulse the proposed limit would be about 158 dB for 50 impulses. Price also reported that for the cat ear exposed to 60 impulses from a rifle (350 μsec A-duration, 2.8 msec B-duration), the onset of PTS was calculated to begin at about 140 dB. The proposed criterion would have rated this exposure tolerable at 151.5 dB. The 11- to 14-dB differences between the proposed limits and the above data in part reflect species differences that are probably related in a systematic manner to the impulse spectrum and in part may reflect the different criteria used in the comparison of the animal data to the curve of the proposed criterion; i.e., criterion levels of TTS for the latter and the onset of PTS for the former. It is reasonable to conclude that at least for these impulses the chinchilla and cat are more susceptible than humans. This figure of 11 dB to 14 dB is interesting. If one compares the results from asymptotic threshold shift experiments in humans and chinchillas using continuous noises (Mills et al., 1979), a similar figure for the relative susceptibility between human and chinchilla is predicted. While this may simply be fortuitous, considering the very different nature of the exposures and experimental paradigms, it does indicate that there are probably systematic and quantifiable differences between the two species that, if explored, could lead to methods for extrapolating from animal to human responses to impulses.

During the 1970s a series of studies was carried out by Pfander and his associates in West Germany using protected and unprotected human subjects. Their results are embodied in a DRC proposed by Pfander (1975) and

Pfander et al. (1980). Despite differences in methodology, the DRCs proposed by CHABA and by Pfander intersect at around 150 dB peak SPL, and for a limited range of temporal and peak pressure variables over 150 dB, the CHABA curve is more conservative. A detailed comparison can be found in a North Atlantic Treaty Organization report (1987).

In 1976, interest in the hazards of impulse noise exposure was revived within the U.S. Army due to problems associated with impulse noise exposure from heavy weapons. In the early 1980s some of the first human studies in the United States using high-intensity impulse noise produced by weapons were undertaken by Patterson et al. (1985, 1987). These studies involved protected human volunteers, but they failed to establish a limit for exposure to heavy weapons when good hearing protection is used. The protection used in these two studies was adequate to prevent TTS in gun crews exposed to the maximum levels of weapon noise that were produced.

This renewed interest on the part of the U.S. Army has led to a substantial increase in the amount of animal model data available. Price and Kalb (1991), for example, after analyzing a considerable body of animal data, have developed a mathematical model to evaluate the hazard to hearing from high-level impulses. The basic concept is of modeling the transfer function between free-field pressure and damaging processes within the cochlea. Free-field waveforms serve as an input to the model that calculates the head-related transfer function, the middle ear transfer function, and the resulting stapes displacements (including nonlinearities) and computes basilar membrane displacements. Hazard to the ear from a particular impulse is calculated as a function of the number and amplitude of the displacements. Such a calculation provides physical insight into the mechanical processes that might be operative and can yield an estimate of hazard as well. Patterson and Hamernik (1992), using synthetically generated impulses presented to chinchillas, have derived a spectral weighting function that shows that energy carried by impulses at low frequencies should be deemphasized up to 10 dB more than that produced by the A-weighting function. Their weighting function when applied to the sound exposure level (essentially an energy measure) unified a broad range of results from impulse noise exposures in the chinchilla.

In 1987, following several meetings over a six-year period, the North Atlantic Treaty Organization (NATO) Study Group RSG-6 of Panel 8 prepared a review document entitled "The Effects of Impulse Noise" (North Atlantic Treaty Organization, 1987). To a large extent the charge of that group as well as their conclusions were similar to those of the working group that produced this report. In an eight-point summary statement the NATO report emphasized the hazards to the auditory system associated with impulse noise exposures and in point IV states that: "None of the existing national Damage Risk Criteria (DRC) for impulse noise are in complete agreement with all the data that have been reviewed by RSG-6. In order to fully account for these data, factors such as frequency weighting, temporal distribution of the impulses, growth of hazard with exposure, intersubject variability in susceptibility for impulse noise and protection afforded by various hearing protectors should be considered. At present, more data are required to be able to address these factors. Until these data become available, the current criteria should continue to be used." The criteria that were reviewed can be found in Smoorenburg (1982), CHABA (1968), Pfander (1975), and Pfander et al. (1980). The NATO report further emphasizes the paucity of data available for use in DRC revisions as well as the uncertainty of which physical parameters of the impulse exposure are the best predictors of hazard.

For impulse noise of moderate levels, standard relations between hearing loss and exposure have been established. In 1981, at a meeting of the leading researchers of impulse noise, a consensus was reached to use A-weighted Leq to assess moderate impulse levels up to 145 dB at the ear (Von Gierke et al., 1982). The results of this meeting were incorporated in the draft standard ISO 1999. In 1986, using the same concept and data of the ISO 1999 draft standard, the American National Standards Institute (ANSI, S3.28, 1986) published a draft standard for evaluating intense sound with A-weighted sound pressure levels above 120 dB and peak C-weighted sound pressure levels below 140 dB. This standard was intended to apply to industrial and recreational impulse noise for which levels were below those addressed by the 1968 criterion proposed by the CHABA working group. The ANSI standard uses an 8-hour, A-weighted Leq of all noise between an A-weighted level of 75 and approximately 140 dB as the indicator of hazard. The working group that developed this standard made a deliberate decision not to try to apply it to higher-intensity impulse noise because of a lack of data and a lack of a general consensus on how to estimate hazard at the higher levels. The ISO standard is based on a Noise-Induced Permanent Threshold Thrift (NIPTS) to sound exposure relationship for the unprotected ear. The suggestion and interpretation that the ISO and ANSI standard could be used for exposures with a hearing protector if the C-weighted peak under the protector was below 140 dB was made by several members of the ANSI committee but not accepted by all. With the approval of ISO 1999 in 1990 (by over 75 percent of the ISO member bodies), a second standard became available to relate noise-induced hearing loss to the A-weighted Leq. One of the benefits of these standards is that they integrate the hazard from exposure to impulse noise with exposure to steady noise. However, they are generally not appropriate for use in evaluating impulse noise for the unprotected ear above 140 dB peak SPL. The charge of the Working Group on Hazardous Exposure to Impulse Noise was to review the 1968 CHABA criterion; thus a detailed evaluation of standards such as ANSI or

ISO was not attempted. However, extension of the 1968 CHABA criterion to impulses below 138 dB peak SPL is definitely not recommended. For simplicity, the working group recommends that the 138 dB level be raised to a C-weighted peak of 140 dB so there is a clear demarcation between the region of application of standards such as ISO 1999 and the 1968 CHABA criterion.

In summary, the few data relevant to the validity of the 1968 CHABA proposal do support the general form of the basic peak level versus B-duration curve for small arms fire, and at least do not deny the accuracy of correction factors for number of impulses and angle of incidence. The 5-dB correction for a decade change in number should be used with caution when extrapolating to more than 100 impulses, since there are limited experimental data to justify this trading relation. It should be noted that in the original Coles et al. (1968) paper the authors state: "Where exposure is to occasional, single impulses only, it seems reasonable to raise the limits somewhat, and an estimate of 10 dB has been agreed upon." The 1968 CHABA report has taken this estimate and extended it without benefit of experimental data to cases in which the number of impulses can be as high as 1,000. Although the A-duration limit appears to be in error, both in form and in specific value, the requirement that B-duration be used in predicting hazard has rendered that problem somewhat academic.

THE QUESTION OF REVISION OF THE CRITERION

The 1968 criterion proposed by CHABA clearly needs modification, but the nature of the necessary changes is not obvious. At the very least, some parameter reflecting the spectral distribution of energy in the pulse must be incorporated and methods for handling mixtures of various impulses, numbers of impulses, temporal spacing of impulses, hearing protection, etc., must be developed. With this in mind, perhaps the most sensible course would be to abandon the criterion and its progenitor, the Coles et al. (1968) proposal, reassess both the data on which they were based and the newer data cited above, perform the necessary experiments to extend knowledge to cover the full range of gunfire, and develop a completely new proposal. If this course is adopted, a series of issues must be addressed in turn.

Criterion

Some measure of TTS in humans remains the most practical criterion response. Although prevention of PTS is the ultimate objective, it is unlikely that any relevant data on PTS will be gathered in humans in the foreseeable future. Use of either TTS or PTS in animals always raises the question of extrapolation to humans by means of correction factors, apart from the possibility that the relation between TTS and PTS may not be the same for the animal in question as for humans. For example, Price and Wansack (1989b) found that in the cat, even moderate values of the group mean TTS measured 1 hour after exposure to impulse noise did not fully recover. In the chinchilla, higher levels of TTS produced by high-level impulses show almost no recovery for a period of several hours (Hamernik et al., 1974). Indeed, the threshold shift induced by impulse noise may actually increase in the first few hours after an exposure that produces permanent damage (Luz and Hodge, 1971; Hamernik et al., 1988). A similar phenomenon has recently been demonstrated in humans by Dancer et al. (1991). Thus, while the best basic criterion response remains reversible TTS in the normal-hearing human, animal studies are useful in exploring parameters and the relations among them. Since the animal model offers data that cannot be obtained in human studies, and phenomena seen in animal models often have their parallels in the human response, animal models should be used to complement human research and, conversely, human studies may need to be designed to confirm or deny results from animal studies. For all human studies, however, agreement must be reached on the questions of the magnitude of the criterion TTS, whether it should be measured two minutes after exposure or at some other time, and in what fraction of ears this shift can be tolerated. Once these decisions are made, various experiments should be designed to determine the relation among various impulse exposure parameters and the criterion TTS.

Exposure Parameters

Energy

Despite years of sporadic experimentation and continuous speculation, no way of describing different gunfire impulses with a single measure has proved to be successful in predicting relative hazard. Obviously, hazard depends on both sound pressure (P) and some function of time (t); however, attempts to show that a constant hazard from gunfire is given by some simple combination of these variables such as $\int P^x dt$, especially when $x = 2$ (the equal-energy principle), have usually given negative results (Henderson and Hamernik, 1986; Danielson et al., 1991), even when the energy has been A-weighted.

The attractiveness of the use of A-weighted energy or in fact any type of an energy approach (in the form of $L_{eq(t)}$, the "equivalent level over time t") as a unifying exposure index lies in its simplicity. One of the first attempts in the early 1970s to define the relation between hazard and number of impulses (Rice and Martin, 1973) resulted in a suggestion of a trading relation of 2.7 dB per doubling of B-duration or of N, a value close to the 3 dB of the energy principle. This suggestion was an outgrowth of an attempt by Atherley and Martin (1971) to show that the hazard of impact noise might be adequately predicted by "total immission" ($L_{eq(24h)}$ weighted by years of exposure); Rice and Martin were exploring the possibility that the energy principle might even be applicable to impulse noise. This effort culminated in a proposal (British Occupational Hygiene Society, 1976) that in the United Kingdom, all noises, including impulses, should be evaluated in terms of their immission, at least for peak levels up to 150 dBA. Since there were no hard data contradicting the use of A-weighted energy as a practical parameter in assessing hazard to human hearing from impulse noise, the principle quickly gained widespread acceptance in Europe, with various international groups proposing a limiting energy of $L_{eq(8h)}$ of 90 dBA (Direction Technique des Armements Terrestres, 1983) or 85 dBA (Smoorenburg, 1982; von Gierke et al., 1982; Dancer, 1983). One of the convenient features of equal energy is that an $L_{eq(8h)}$ of 85 dBA corresponds to an $L_{eq(1\ msec)}$ of 160 dBA, a value in good agreement with the 1968 proposal limit of 163 dB for a single impulse of 1-msec duration. only if exchange rate is 6.47 (?)

However, it is clear that energy is not the sole determinant of hazard from high-intensity gunfire. Price (1985b, 1986) has shown, for example, that in order to produce a 40-dB TTS in cats, an A-weighted energy flux of 400 J/m² would be needed for howitzer fire, 10 J/m² for rifle fire, but only 0.4 J/m² for primer noise. Although there is some question regarding the magnitude of the last figure (Price, 1991), the data emphasize the need for a change from the A-weighting function for high-intensity impulses. That a frequency weighting function other then A-weighting can organize a diverse set of impulse noise exposure data has been demonstrated by Patterson and Hamernik (1992). Another failure of the energy principle was reported by Chatham (1985), who exposed guinea pigs to different frequency tone bursts a few cycles in duration in an attempt to mimic impulse noise. She found that the same $TTS_{(3h)}$ was produced by 1-, 3-, or 10-msec tone bursts of a given amplitude, despite a 10-fold range in energy.

Perhaps when the dynamic transfer function of the outer and middle ears is accurately known so that a valid prediction can be made of what happens to an impulse waveshape as it proceeds through the middle ear and enters the cochlea, some form of a spectrally weighted energy or $\int P^x dt$ will prove to be a more useful descriptor. A number of studies (Stevin, 1982; Kalb and Price, 1985; Chatham, 1985; Price and Kalb, 1987, 1988) have attempted to establish a model of the middle ear for this purpose. It is likely, for example, that above some level, acoustic waves are subjected to peak clipping by the eardrum or by the annular ligament of the stapes (Price, 1974). These and other (perhaps protective) nonlinearities (Sommer and Nixon, 1973) need to be understood before appropriate descriptive metrics of the impulse stimulus can be developed for use in exposure criteria.

Spectral Considerations

Many of the ambiguities or difficulties with the A- and B-duration approach may be resolved by developing a spectral metric for the evaluation of the impulses in the frequency domain. Such a metric would have the advantage that all the time variables for a single impulse would be considered and the number of variables for a single impulse reduced to essentially two: impulse peak and spectral energy (considering the results of Patterson et al., 1992, and Danielson et al., 1991, impulse peak may need to be retained as a separate variable even though the spectrum incorporates the peak). That such an approach was not originally taken by Coles et al. (1968) because of instrumentation limitations can be inferred from their paper. Price (1979) and Patterson and Hamernik (1991) have pursued this approach. The latter have developed a weighting function that can unify a diverse set of animal data by using a spectrally weighted energy measure.

Peak Pressure Level

Maximum positive overpressure is one of the most commonly used parameters for describing an impulse. The utility of this measure in future criteria needs to be evaluated in light of the peak limiting or other protective nonlinearities described by Price (1974). A particularly instructive set of results published by Patterson et al. (1986) used impulses whose peak and total energy could be varied but whose spectra were kept constant. Their conclusion was that "these results indicate that peak pressure is not a sufficient indication of auditory hazard; however, energy alone is not a sufficient indicator either." These results coupled with the ability of an energy-weighted measure (Patterson and Hamernik, 1991) to organize impulse noise data suggest that a weighted energy measure may provide a better index than peak pressure when evaluating hazards.

Duration

Temporal measures of the impulse waveform were considered important by the authors of the original CHABA criterion. Their insights led to the criterion's being defined in terms of the peak level and the A- and B-durations. Considering that the basic instrument used in the measurement of the impulse at that time was the cathode ray oscilloscope, these two metrics of duration and peak were relatively easily obtained. It is evident from the Coles et al. (1968) text that the authors were aware that these three variables provided at least a qualitative estimate of the spectrum and energy of the impulse. With current digital instrumentation it is unlikely that a criterion in terms of these two often ambiguous temporal variables would

THINGS to do TODAY

DATE

		Done	To Do
1	if we use the factor of 6.67 log, we also		
2	get -23.5 for 157		133.5
3	-26.6 for 160		133.4
4	- 6.67 for 140		133.3
5			
6	Modified SEL Criterion		
7	is 135 dB - 100 impulses		
8	time duration adjustment = 6.67 log		
9	number of pulse " = 5 log		
10			
11	Leq 1 msec (160) dB ⇒ SEL		
12	adjusted 5 log 140		
13	6.67 log 133.4		
14	10 log 120		
15	Leq(8h) 85 dB log for 8 hrs = 4.46 x10 = 44.6		
16	85 SEL = 129.5		
17			
18			
19			
20			

EPA Form 1300-19 (2-83)

THINGS to do TODAY

DATE

take 150 . duration = 3.5 msec
correction factor log = -2.6 × 5 = 13

		Done	To Do
1	~~Henry Houze~~ 150-13=	137	dB
2	~~614 H St N.W~~		
3	~~Rm 614~~		
4	~~20001~~		
5			
6			
7	157 0.3 msec 1/3333 sec		
8	log 3333 = 3.5 10 log = 35		
9	and SEL = 157-35 = 122	dB	
10	Take 140 dB for 100 ms		
11	SEL correction = -10 dB		
12	and SEL = 130 dB		
13	take 160 dB for 0.1 msec correction factor = -40 dB		
14	and SEL = 120 dB		
15	for 100 pulses - correction factor		
16	= 5 log (100/x)		
17	perhaps we should use 5 log as correction/10		
18	then correction factor for .3 msec = 5 × 3.5	= 17.5	
19	for .1 msec = 5 × 4	= 20	
20	for 100 msec = 5		

EPA Form 1300-10 (2-83)

and we get SEL = 140, 140, and 135 dB respectively have evolved. In order to estimate a B-duration, for example, some aspect of the envelope of the signature such as "the time after impulse onset until the envelope is Y dB down from the peak" was required, but the optimum value of Y was not determined. The value of 20 dB down that defines B-duration was apparently chosen arbitrarily by Coles et al. because it represented a pressure ratio of 1/10. Almost all subsequent proposed limits have agreed that a smaller value such as 10 dB or 8.7 dB (pressure ratios of $1/\sqrt{10}$) and 1/e respectively) should be used because the contribution to the total energy of the impulse by elements between 10 and 20 dB down would be negligible, unless some form of a protective nonlinearity, such as peak clipping, occurs so that secondary peaks might be just as hazardous as primary peaks by the time they reach the inner ear. Considering that such nonlinear effects are most likely introduced by elements of the conductive chain (Price and Kalb, 1991) and that they may radically alter the waveform arriving in the cochlea, the suggestion has been made, based on theoretical modeling, that it might be more useful to establish a limiting band of pressure disturbance about the baseline, DP^+ and DP^- (not necessarily symmetric) and use this "clipped" measure of the entire signature to obtain energy and spectral information for application to criteria design.

For most of the impulses produced by weapon discharges, the rise time of the impulse is that characteristic of the shock front that typically leads the pressure disturbance if the peak is in excess of roughly 140 dB. For all practical purposes it can probably be considered zero or, if the frequency domain approach is used, rise time will be subsumed into the spectrum and appear as part of the high-frequency energy or more probably as a high-frequency manifestation of the microphone rise time. There is as yet no experimental evidence that a shock front leading the impulse per se has any greater or lesser effect on trauma beyond its contribution to energy at the high frequencies. With the above in mind, a spectral representation of the impulse along with peak and energy metrics is easily obtained with contemporary instrumentation and may avoid completely the need to consider temporal parameters of the single impulse separately.

Number of Impulses

Once limits of exposure to single impulses have been established, subsequent experiments should examine the rate of decrease of permissible peak level as N increases from 1 to 100 or 1,000, in order to derive correction factors for N that are based on something more substantial than Coles et al.'s comment that a correction of 10 dB in going from 100 impulses to a single one "was agreed upon." While one would hope that the correction factor in dB will turn out to be a linear function of either N or log N, adequate information is not available to determine this function for up to

1,000 impulses. There are results from animal experiments (Liang, 1992) and with humans using simulated gunfire (McRobert and Ward, 1973; Ertel, 1973) that indicate that the function may not be linear. Patterson et al. (1985), in contrast, demonstrate a linear relation over a 15-dB range of peak SPLs, implying that the hazard from increasing the number of impulses may accumulate on an energy basis. However, there are relatively few data available, especially for exposures for which N > 100, from which a definitive trading relation for N can be established.

Mixture of Impulses

Armed with knowledge about the trading relation between peak level and N, it would be possible to infer the effect of a mixture of impulses in which all parameters except one are held constant, and then test this predicted relation by suitable experiments. Whether the effect would be dominated by the highest levels or instead depend on an equivalent level or median peak level, for example, would have to be determined. Development of an equation in which the permissible gunfire "dose" is defined in terms of numbers of impulses, evaluated as the sum of several partial doses, is a worthwhile goal, although one not likely to be realized in the near future.

Data relevant to this issue were recently published by Patterson et al. (1991). The experiment consisted of presenting a series of low peak (138 dB) impulses followed by a series of high peak (146 dB) impulses and then reversing the order of presentation. The group mean data showed differences between the two impulse presentations. However, because of the large variability and small sample size, the difference was not statistically significant. This experiment, however, does indicate the possibility that there may be problems with a "proportional dose" approach. Further experimentation to study the possible interaction between impulse noise and steady noise should also be undertaken, as the evidence so far is equivocal. Hamernik et al. (1974) reported extensive damage in chinchillas exposed to a combination of 95-dB-SPL steady noise and 50 158-dB-SPL spark discharge peaks, even though either noise alone produced little effect. And yet a combination of a series of 300 impulses of simulated gunfire at a peak level of 139 dB and 90-dB-SPL steady noise produced about the same TTS in humans as either one alone (Ward, 1988).

Temporal Spacing

If impulses follow each other so rapidly that the acoustic reflex is maintained, the hazard is considerably reduced. Other than that, the effect of interstimulus interval is not well understood, except for the observation that beyond 10 seconds or so, both TTS and PTS will be reduced as the interval increases (Perkins et al., 1975). More recently Hamernik et al. (1991) concluded that because of the large intersubject variability, systematic effects of interstimulus interval over a range 0.1 min through 10 min could not be discerned. Danielson et al. (1991), using synthetic impulses of 150 and 135 dB peak SPL, showed that there were clear differences in effect related to the temporal order of the impulse presentation. Since all of their exposures had equal energy, these results further show that under certain circumstances energy considerations are not sufficient to predict hazards. A correction factor for interstimulus interval may be nonmonotonic, being larger for both shorter and longer intervals than for 1-10 seconds.

Modification of Exposure Limits for the Protected Ear

Obviously, a correction factor associated with the use of some sort of hearing protective device is unlikely to be simple, because most protectors do not reduce all frequencies equally. In general, low frequencies are less attenuated by the hearing protective device than high frequencies, so that in addition to reducing the peak level, the device produces changes in all dimensions of the impulse reaching the inner ear, including A-duration, B-duration, and especially rise time. The increase in rise time beneath the hearing protective device indicating the absence of a shock front (i.e., a filtering out of high-frequency energy) may alone account for the fact that when deeply seated insert foam protectors are used, cannon fire, producing peak levels of up to 181 dB SPL, fails to produce the slightest amount of TTS in Army personnel (Patterson et al., 1985). Even triple-flange protectors reduced the TTS from howitzers to values so small as to be meaningless (Hodge et al., 1979). These early results are consistent with the recent data on protected human subjects presented by Johnson and Patterson, (1992) showing low levels of TTS from impulses as high as 190 dB in the free field. Clearly, the application of a single-number correction factor such as the noise reduction rating of a hearing protective device will underestimate the amount of reduction of hazard actually obtained.

RECOMMENDATIONS

Use of the 1968 CHABA Criterion

The 1968 damage-risk criterion proposed by CHABA may still be applied in many circumstances and can be expected to provide reasonable answers. However, the following limitations or restrictions are strongly recommended:

- The 1968 damage-risk criterion proposed by CHABA should be applied only to small arms fire with peaks in excess of 140 dB (i.e., weapons of approximately .22 through .50 calibre and shotguns) and to individuals with unprotected ears.
- Until a suitable replacement for the 1968 criterion is formulated, the A-duration variable should be deleted for the reasons discussed.
- Since the effects of large numbers of impulses are not known, the trading relation of 5 dB of peak for a tenfold change in number should be applied with caution above 100 impulses. This criterion should not be applied to other types of impulses.
- The 1968 criterion should not be extrapolated to impulses with peak levels below 140 dB for more than 100 impulses by using the 5-dB decrease in level for a tenfold increase in number. For peak SPLs at the unprotected ear of 140 dB and below, the A-weighted energy approach as standardized in ISO 1999, or ANSI S3.28, 1986, may be a practical approach for military and nonmilitary application.
- The 1968 criterion should not be used for low-frequency impulses such as air bags, sonic booms, rapid pressurization, etc.
- The 1968 criterion should not be used for assessing the hazard of a waveform under a hearing protector.

Use of Other Criteria

Other impulse noise criteria, primarily those developed or used in Europe, have been shown to arrive at approximately the same ranges for safe exposure but suffer from the same lack of hard data. Therefore, these criteria are not recommended as a replacement for the 1968 CHABA criterion.

Needed Research

Efforts should be made to replace the 1968 criterion with a criterion based on data obtained from systematic human and animal experimentation and supported by a modeling effort.

Human Research: Since it is unlikely that sufficient human PTS data will ever become available, the most practical method to arrive at safe exposure conditions is to obtain TTS data from human experiments despite the known limitations of the various relations between TTS from different exposures and the relations between TTS and PTS. Well-designed human TTS studies are required to produce the data base needed to arrive at more generally applicable impulse noise exposure criteria and to validate any predictive models.

Animal Research: Animal experiments represent the best approach to understanding the complex effects of different peak levels, average levels, spectra, durations, temporal variables, etc. However, animal data cannot be of quantitative help in arriving at human exposure criteria until strategies for extrapolating from animal to human effects are developed. This is a goal that should be pursued. The following areas of research should also be emphasized in future studies:

- Establish which parameters of an impulse exposure should be measured and how they should be combined to provide as simple an index of hazard as is feasible.
- Establish the effects of impulse spectrum on hazard.
- Establish the efficiency of various hearing protective devices in reducing hazard.
- Establish the contribution of various protective nonlinearities such as the effect of the middle ear reflex, peak clipping, etc.
- Establish a trading relation between number of impulse presentations and other metrics of hazard.
- Establish procedures for evaluating mixtures of impulses.
- Establish procedures for assessing the effect of temporal spacing of impulses.

Modeling: A promising approach to understanding the hazard to human hearing from defined impulse exposures is that of modeling the human ear based on biophysical, human, and animal response data including level-dependent nonlinearities. Despite some promising results, the approach needs further maturation before it can be more generally applied.

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