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**An Experimental Basis for the Estimation  
of Auditory System Hazard  
Following Exposure to Impulse Noise  
(Reprint)**

**By**

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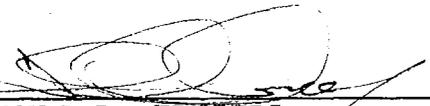
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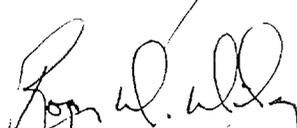
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19. ABSTRACT (Continue on reverse if necessary and identify by block number) The energy spectrum of a noise is known to be an important variable in determining the effects of a traumatic exposure. However, existing criteria for exposure to impulse noise do not consider the frequency spectrum of an impulse as a variable in the evaluation of the hazards to the auditory system. This report presents the results of three studies that were designed to determine the relative potential that impulsive energy has in causing auditory system trauma. Four hundred and seventy five (475) chinchilla were used in these experiments. Pre- and post-exposure hearing thresholds were measured on each subject. In the first study, the noise exposure stimuli consisted of six different computer-generated narrow band tone bursts having center frequencies located at 0.260, 0.775, 1.025, 1.350, 2.450, and 3.550 kHz. Each narrow band exposure stimulus was presented at two to four different intensities. An analysis of the audiometric data allowed a frequency weighting function to be derived. This weighting function de-emphasizes low frequency energy more than the conventional A-weighting function. In the second study, the exposures consisted of			
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two types of broad band computer synthesized impulses. Subjects were exposed to 100 impulses at a rate of 1-per-3-seconds. Each type of impulse was presented at 3 intensities. The third study used impulses generated by three different diameter shock tubes. Subjects were exposed to 1, 10, or 100 impulses at one of three intensities. The results of the second and third studies were interpreted using the weighting function derived from the first study. The hearing loss from all three studies is a linear function of the weighted SEL calculated using the weighting function, derived in the first study.

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## CHAPTER 30

# *An Experimental Basis for the Estimation of Auditory System Hazard Following Exposure to Impulse Noise*

JAMES H. PATTERSON, JR.  
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There are a number of different suggested standards for exposure to impulse/impact noise (Coles et al, 1968; OSHA, Dept of Labor, 1974; Smoorenburg, 1982; Pfander et al, 1980). Although each of these criteria has its proponents, none of them is in complete agreement with existing data (Smoorenburg, 1987). What is needed is a new criterion. Unfortunately, there is an extremely limited empirical database on which a new standard can be built. The difficulties associated with generating such a database are compounded by the extremely broad range of high-intensity noise transients that exist in various industrial and military environments. For example, in industry, impacts with variable peak intensities and a reverberant character often occur. At the other extreme, the diverse military weapon systems produce impulses that originate as the result of a process of shock-wave formation and propagation following an explosive release of energy. These waves, which can have peak levels in excess of 180 dB, can be either reverberant or nonreverberant, depending on the environment in which they are encountered. Trying to develop a single standard to cover this broad range of "acoustic" signals is a formidable task.

Existing or proposed exposure criteria generally lack specific consideration of the frequency domain representation of the impulse. This point has been raised frequently by Price (1979) and others. However, some deference is given to the spectrum in these criteria, in an indirect manner, through the handling of the A and B duration variables.

A more direct spectral approach to the evaluation of impulses and impacts was proposed by Kryter (1970). His suggestions, although based on sound reasoning, never gained acceptance. The Kryter approach was attractive in its ability to predict the amount of temporary threshold shift measured 2 minutes after exposure ( $TTS_2$ ) to a noise transient. However, this approach was limited to situations in which the  $TTS_2$  was not excessively large or, alternatively, the levels of the transient in any given frequency band were not excessive.

Price (1979, 1983, 1986) has built on and extended the Kryter approach by considering the spectral transmission characteristics of the peripheral auditory system. Price's reasoning led to the following conclusions: (1) There is a species-specific frequency,  $f_0$ , at which the cochlea is most vulnerable and that impulses whose spectrum peaks at  $f_0$  will be most damaging. This would appear to be true, according to Price, regardless of the distribution of energy above and below  $f_0$ . For man, the suggested frequency is 3.0 kHz; and (2) Relative to the threshold for damage at  $f_0$ , the threshold for damage should rise at 6 dB per octave when  $f_p$  is greater than  $f_0$  and at 18 dB per octave when  $f_p$  is less than  $f_0$ , where  $f_p$  is spectral peak of the impulse. Thus, a model for permanent damage was developed that is amenable to experimental testing. In subsequent studies, Price (1983, 1986) has tried to relate, with varying degrees of success, experimental data obtained from the cat to the predictions of this model. More recently, Hamernik et al

(1990) and Patterson et al (1991) have reported on an extensive series of parametric studies in which the spectra of the impulses were varied. A review of the literature indicates that, except for the studies mentioned above, there are few other published results obtained from experiments specifically designed to study the effects of the spectrum of an impulse on hearing trauma.

This chapter presents an analysis of the Patterson et al (1991) data from which a spectral weighting function is derived. This weighting function will then be applied to the blast wave data of Hamernik et al (1990) and to the synthetic impulses from Patterson et al (1986) in order to develop a relation between the permanent threshold shift (PTS) and the sound exposure level (SEL). The intention here is not to present a set of conclusive results, but rather to illustrate a new approach to the analysis of this type of experimental data. It is an approach that develops a direct relation between frequency-specific measures of PTS and the frequency domain representation of the impulse. The results of this approach can be related directly to the Price (1983) model and can be used to estimate the permanent effects of a traumatic impulse noise exposure in a manner similar to that approach proposed by Kryter (1970) for estimating temporary threshold shift (TTS) after an impulse noise exposure.

TABLE 30-1 Exposure Conditions for the 20 Groups of Animals Used for Series I Exposures

CF (Hz)	PEAK SPL (dB)	TOTAL SEL (dB)
260	139	132.5
260	146	139.8
775	134	124.8
775	139	129.4
775	144	134.8
1025	129	119.8
1025	134	124.2
1025	139	129.1
1025	144	134.6
1350	129	119.8
1350	134	124.2
1350	139	129.0
2450	129	120.6
2450	134	124.9
2450	139	129.6
2450	144	135.0
3550	124	113.0
3550	129	119.9
3550	134	124.2
3550	139	129.5

## Methods

The noise-induced permanent threshold shift (NIPTS) data presented in this report were acquired from 475 chinchillas exposed to high levels of impulse noise. Audiometric data on each animal were obtained using either a shock avoidance procedure (Patterson et al, 1986) or measures of the auditory evoked potential (Henderson et al, 1983). Permanent threshold shifts were computed from the mean of three preexposure audiograms and at least three audiograms taken 30 days after exposure. The behaviorally trained animals were tested at octave intervals from 0.125 kHz through 8 kHz including the half-octave points 1.4, 2.8, and 5.7 kHz. Evoked potential thresholds were measured at octave intervals from 0.5 to 16 kHz and at the 11.2-kHz point. For each animal, measures of compound threshold shift, PTS, and quantitative histology (cochleograms) were obtained. In the analysis that follows, only PTS data will be discussed.

### Series I Exposures (N = 118)

Animals were exposed at a normal incidence (i.e., the plane of the external canal was parallel to the speaker exit plane) to 100 impulses presented at the rate of 1 every 3 seconds. This series of exposures consisted of 20 groups of animals, with five to seven animals per group. The stimuli were narrow-band impulses produced by passing a digital impulse through a four-pole Learner-type digital band-pass filter (Gold and Rader, 1969). Following analog conversion, the signal was transduced through an Altex 515 B speaker in a model 815 enclosure. The filter bandwidth was independent of center frequency, with steep attenuation outside the passband permitting the synthesis of equal energy impulses at a variety of center frequencies while assuring minimal spread of energy to other frequencies. The center frequencies of the six sets of impulses varied from 260 to 3,350 Hz. The bandwidth of the impulses was approximately 400 Hz. Impulse peaks were varied from 124 to 146 dB. For each of the exposure conditions listed in Table 30-1 the total SEL was computed as follows (Young, 1970):

$$SEL = 10 \log_{10} \int_{-\infty}^{\infty} \frac{p^2(t)dt}{p_r^2 t_r}$$

where  $t_r = 1$  second,  $p_r = 20 \mu\text{Pa}$ . Figure 30-1 illustrates an example of the pressure-time his-

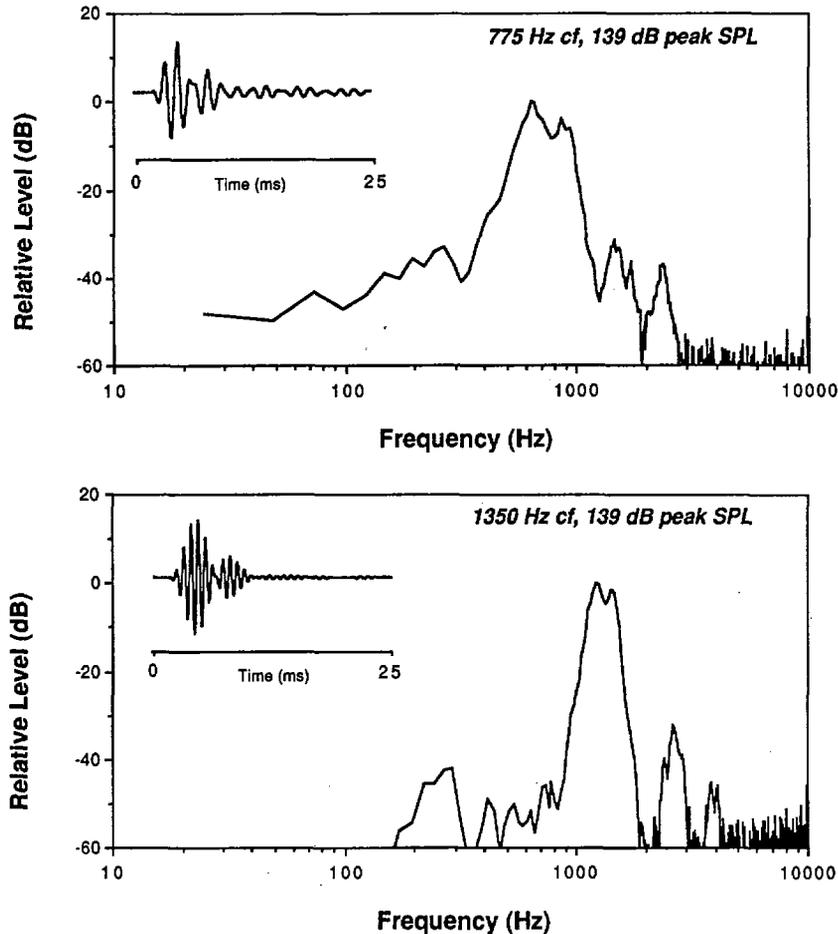


Figure 30-1 Examples of the 775-Hz (A) and 1,350-Hz (B) center frequency impulses of the Series I exposures along with their respective spectra.

TABLE 30-2 Exposure Conditions for the Seven Groups Used for Series II Exposures

WAVE TYPE	PEAK SPL (dB)	TOTAL SEL (dB)	TOTAL P-SEL (dB)	TOTAL P'-SEL (dB)
High Peak	147	130.8	127.6	133.4
Low Peak	139	130.3	127.2	132.9
High Peak	139	123.0	119.9	125.6
Low Peak	131	122.4	119.3	125.0
High Peak	135	119.1	115.8	121.6
Low Peak	127	118.5	115.3	121.0
High Peak	131	115.1	111.9	117.5

tories of the 775-Hz and 1,350-Hz center frequency impulses along with their respective spectra.

### Series II Exposures (N = 42)

Animals were exposed at a normal incidence to 100 impulses presented at the rate of

1 every 3 seconds. There were seven different exposure conditions (Table 30-2) to which seven groups of animals were exposed. Each group contained six animals. Two types (low peak and high peak) of relatively broad-band impulses with identically-shaped amplitude spectra were synthesized digitally (Patterson et al, 1986). The peak sound pressure level (SPL) of the impulses was varied from 127 to

147 dB. Hearing threshold data were obtained using the avoidance conditioning procedure. Figure 30-2 illustrates the pressure-time histories of typical high- and low-peak impulses along with their common spectrum.

### Series III Exposures (N = 315)

Animals were exposed at a normal incidence to either 1, 10, or 100 impulses, presented at the rate of or 1 every 10 seconds at intensities of 150, 155, or 160 dB peak SPL. All of the above combinations of number, repetition rate, and peak yielded 21 different exposure groups with five animals per group. The impulses were generated by a compressed-air-driven shock tube. This set of 21 exposures was repeated using waves generated by three shock tubes of different diameters that produced blast waves whose spectrum peaked at three different locations of the audible spectrum. The pressure-time traces and spectral analysis of these waveforms are shown in Figure 30-3. In addition, the A-weighted octave band energies are shown in Figure 30-4 so that comparisons could be made for each wave from each source. Because of the high levels of very-low-frequency energy in these blast waves, the resolution at the high frequencies is poor if unweighted energies are plotted. For further details see Hamernik and Hsueh (1990). Table 30-3 summarizes the conditions for the Series III exposures. Only the SELs for the 100-impulse conditions are tabulated. Successive 10-dB adjustments need to be made to obtain the 10-impulse and the 1-impulse SEL values. All animals in this series were tested using the auditory evoked potential procedures.

## Results

The results of each series of exposures are presented separately, and the methods used to analyze the NIPTS data from each series are explained.

### Series I Exposures

For each of the 20 groups of animals that were exposed to the narrow-band impulses, a mean PTS evaluated at 1, 2, and 4 kHz ( $\overline{PTS}_{1,2,4}$ ) was computed, and the groups were compared on the basis of SEL. This data set is shown in Figure 30-5. The group mean PTS

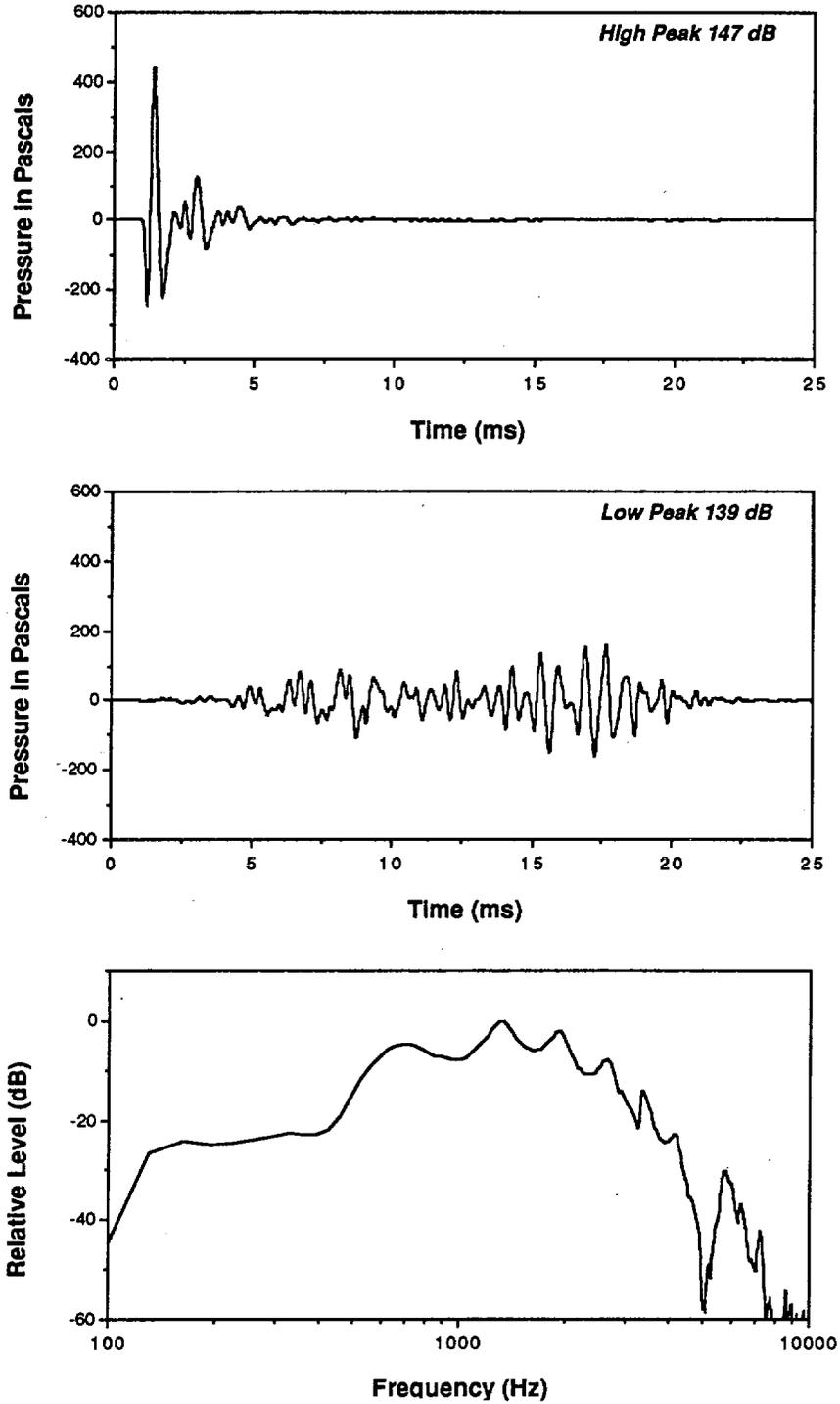
from each set of the two to four groups of animals that make up an intensity series for a specific characteristic frequency (CF) impulse behaves in an orderly manner, with  $\overline{PTS}_{1,2,4}$  increasing in an approximately linear fashion with increasing SEL.

The relative susceptibility to NIPTS is seen to be a function of the impulse center frequency, with the lower-frequency impulses producing relatively little NIPTS even at the higher SELs. A relative frequency weighting function can be derived from the data presented in Figure 30-5 by shifting each frequency-specific data set along the SEL axis the amount that is necessary to collapse the data into a single PTS/SEL function using one of the exposures as a "zero" reference.

Such a data-shifting process was carried out "by eye" to produce a best fit using the 1,350-Hz series of data as the reference point. The amounts shifted were 260-Hz CF impulses, -20 dB; 775-Hz CF impulses, -7.2 dB; 1,025-Hz CF impulses, -4 dB; 1,350-Hz CF impulses, 0 dB; 2,450-Hz CF impulses, -4 dB; and 3,550-Hz CF impulses, +4 dB. The realignment of the data that such a shift produces is shown in Figure 30-6, and the weighting function, thus obtained, is shown plotted (solid line with symbols) in Figure 30-7, where it is compared to the conventional A-weighting function (solid line). The new empirical weighting function is referred to as P-weighting in the legends for these figures. A linear regression through the shifted data set showed a correlation coefficient of 0.89 with a slope of 2.6 dB PTS per decibel P-weighted SEL (P-SEL) and a threshold for the onset of  $\overline{PTS}_{1,2,4}$  of 116 dB P-SEL. The empirical function derived from the narrow-band impulse data is seen to differ from the A-weighting function by as much as 10 dB at the low frequencies. Also evident in this figure is the anomalous behavior of the data point produced by the exposures to the 2,450-Hz, CF impulses.

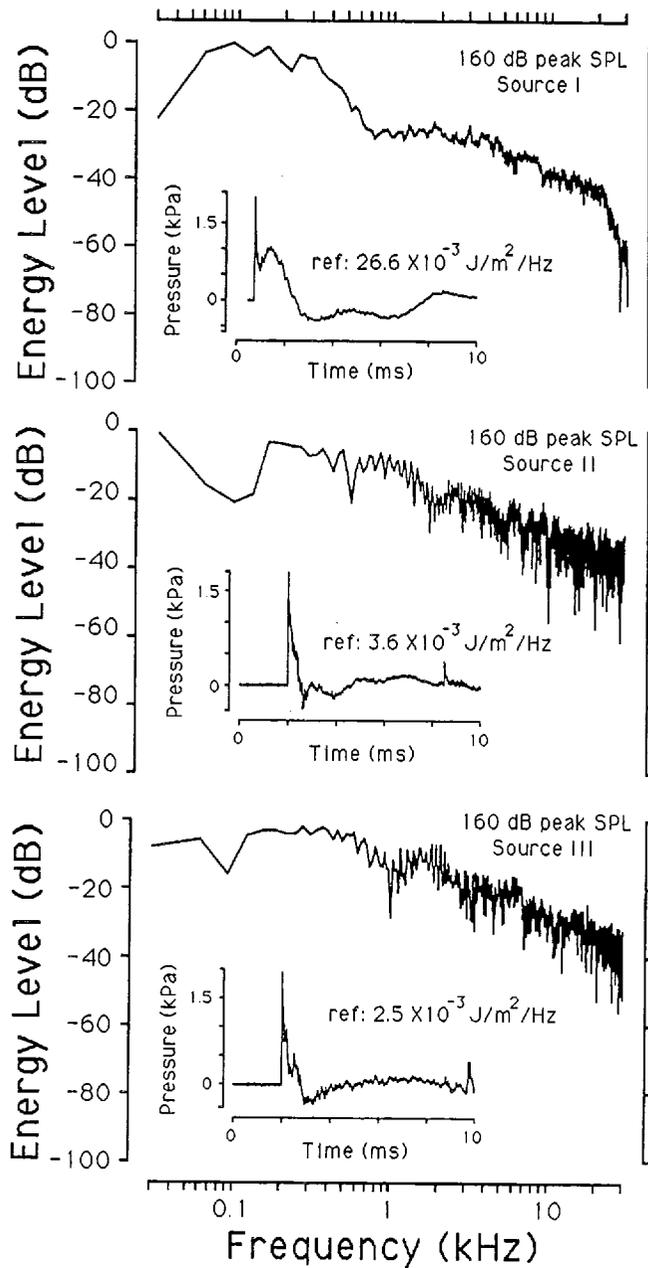
### Series II Exposures

The detailed histologic and audiometric results of this series of exposures have been published by Patterson et al (1985, 1986). The  $\overline{PTS}_{1,2,4}$  data from this series of seven exposures is shown plotted as a function of the SEL and the P-SEL in Figure 30-8. The latter was obtained by applying the empirical weighting function (Fig. 30-7) to consecutive octave bands of the spectrum of the Series II exposures. Also included in this figure are the shifted (or P-weighted) data points from the



**Figure 30-2** Examples of the Series II impulses and their common spectrum. *A*, The high-peaked 147-dB peak SPL impulse. *B*, The low-peaked 139-dB impulse. *C*, The spectrum of each of the above, approximately equal-energy, impulses.

**Figure 30-3** Examples of the 160-dB peak SPL impulses produced by the three different shock tubes and their respective spectra. These waves are typical of those used for the Series III exposures.



Series I exposures. It is evident that the P-weighting function does not have the desired effect of increasing the degree of congruence between the Series I and II exposures. Because the Series II exposures had substantial energy in the 2-kHz region of the spectrum, it was apparent that the effect of applying the empirical weighting function to this region of the spectrum would shift the Series II data points in the wrong direction. However, if the empirical P-weighting function is

extrapolated as shown by the dotted portion of the function in Figure 30-7, and then used to weight the Series II impulses, the agreement between the Series I and Series II data becomes good, as seen in Figure 30-9. A linear regression analysis (solid line) of the entire data set from the Series I and Series II exposures shows a correlation coefficient of 0.91, a slope of 2.5, and an X-intercept of 116 dB. This modified weighting function is referred to as P'-weighting.

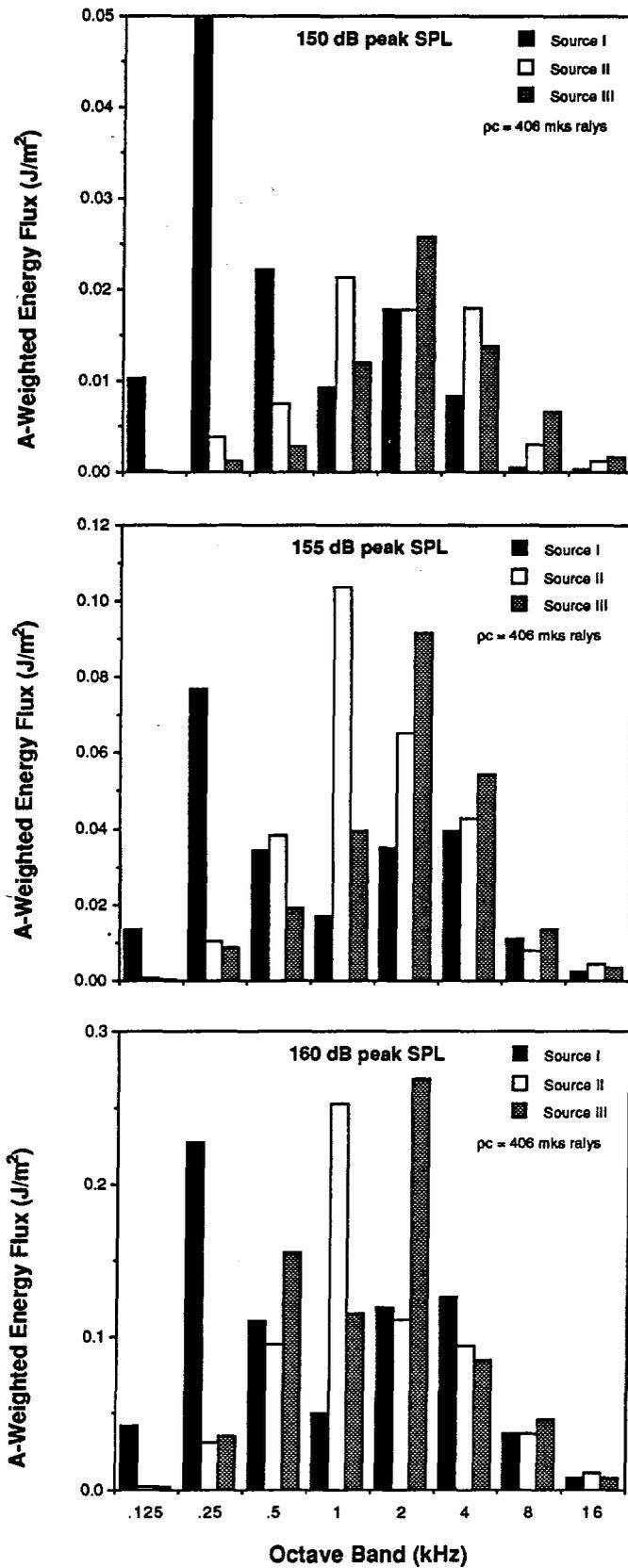


Figure 30-4 A-weighted octave band spectra of each of the waves that were used for the Series III exposures.

TABLE 30-3 Exposure Conditions for the Nine Groups Used for 100-Impulse Series III Exposures\*

SOURCE	PEAK SPL (dB)	TOTAL SEL (dB)	TOTAL P'-SEL (dB)
I	150	140.3	129.2
I	155	141.8	133.6
I	160	146.4	138.8
II	150	131.4	130.3
II	155	136.5	135.3
II	160	140.6	138.6
III	150	129.0	130.8
III	155	135.0	136.2
III	160	139.1	139.9

\*Corresponding SEL and P'-SEL values for the 10-impulse and 1-impulse conditions can be obtained by making the appropriate 10-dB adjustments.

Figure 30-5 The group mean permanent threshold shift (PTS) evaluated at 1, 2, and 4 kHz ( $\overline{PTS}_{1,2,4}$ ) as a function of the total sound exposure level for the six groups exposed to the Series I narrow-band impulses.

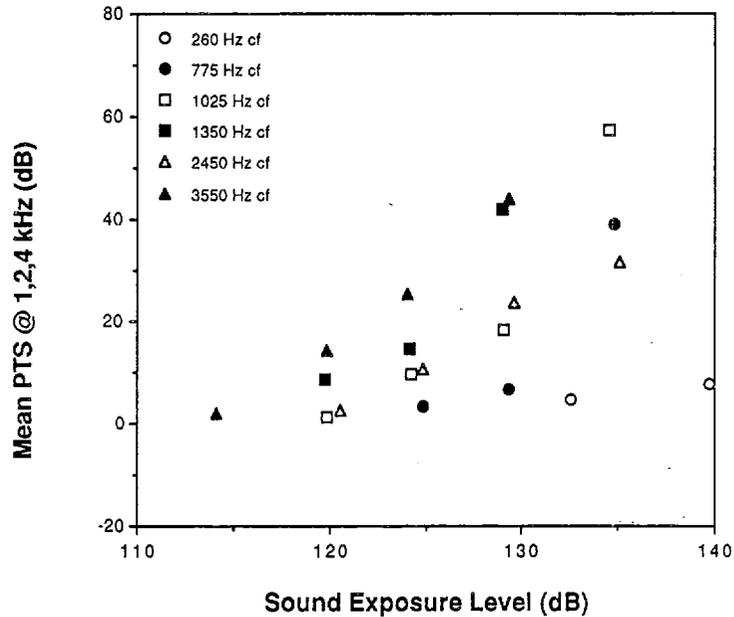
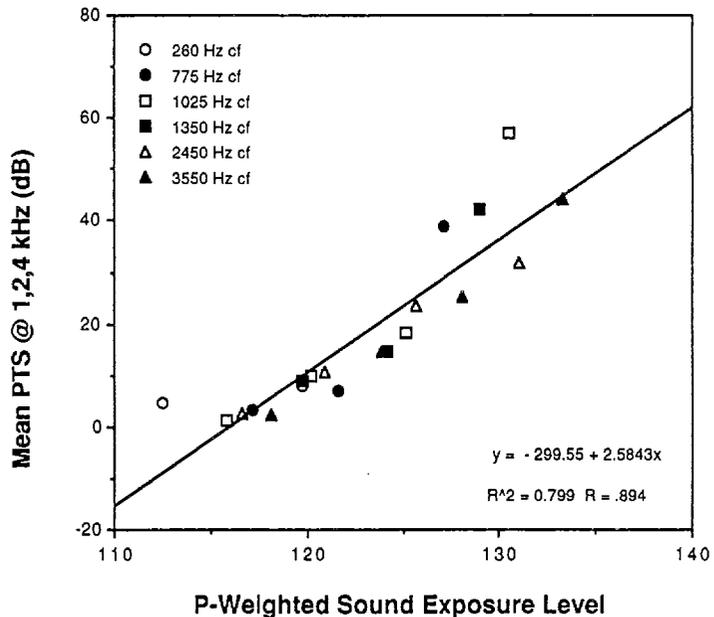


Figure 30-6 The permanent threshold shift at 1, 2, and 4 kHz ( $\overline{PTS}_{1,2,4}$ ) as a function of the empirically-derived P-weighted sound exposure level for all the Series I exposures. The regression line has a slope of 2.6 and an X-intercept of 116 dB.



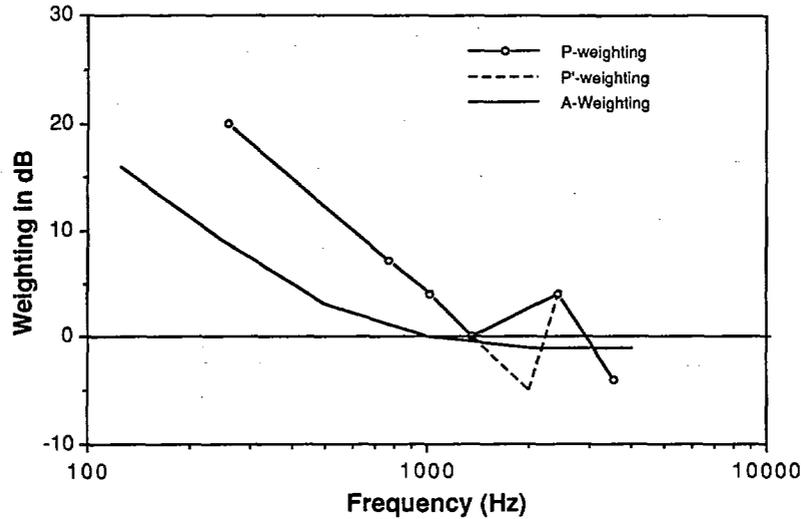


Figure 30-7 The empirical P-weighting function derived from the Series I exposures along with the conventional A-weighting function and the P'-weighting function inferred from the Series II and III experiments.

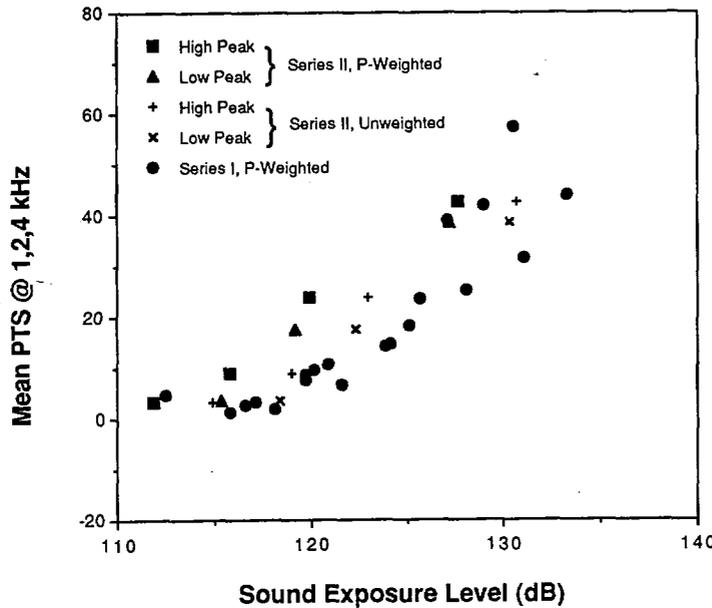


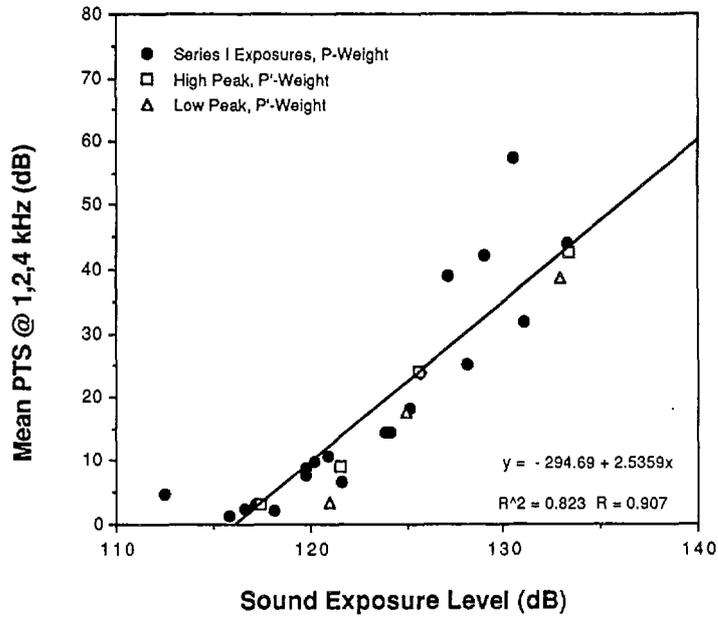
Figure 30-8 The permanent threshold shift at 1, 2, and 4 kHz ( $\overline{PTS}_{1,2,4}$ ) from the Series II exposures shown as a function of unweighted and P-weighted sound exposure level compared to the  $\overline{PTS}_{1,2,4}$  versus P-weighted sound exposure level of the Series I exposures.

### Series III Exposures

One problem that seems to characterize the measurement of PTS following exposure to these high peak levels of impulse noise is extreme intersubject variability. A number of authors have commented on this problem in the past, including Kryter and Garinther (1965) and Henderson and Hamernik (1982). Price (1983, 1986) also reported large inter-subject variability when measuring threshold shifts in cats that had been exposed to blast

waves that were similar to some of the impulses in the Series III exposures. Another problem is the excessive time necessary to run an experimental animal through a complete experimental paradigm of audiometric and histologic protocols, thereby effectively limiting the number of animals in each experimental group and hence the statistical power. On the basis of a preliminary analysis of the PTS data (using analysis of variance), it was apparent that the effects on PTS of the different impact presentation rates were, at best,

**Figure 30-9** Permanent threshold shift at 1, 2, and 4 kHz ( $\overline{PTS}_{1,2,4}$ ) obtained from the Series I and Series II exposures as a function of P- and P'-weighted sound exposure levels, respectively. The linear regression line was computed using all the points shown plotted in this figure. X-intercept = 116 dB; slope = 2.5.

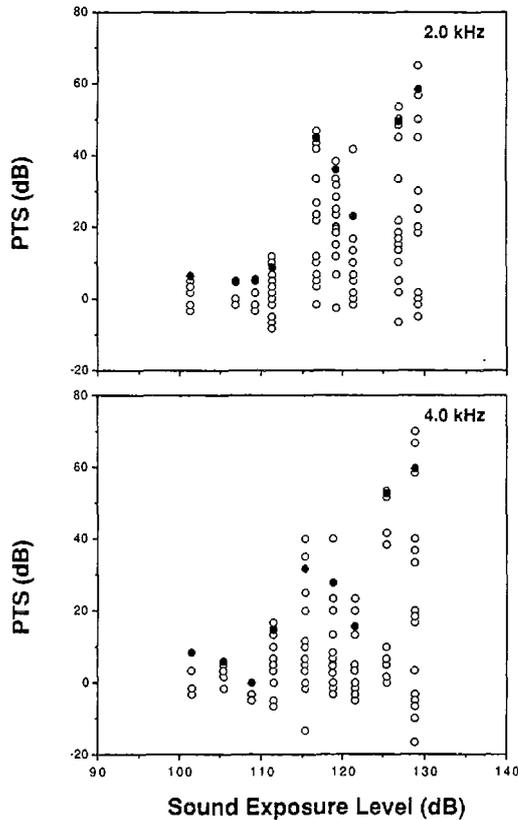


marginal statistical effects. Thus, a decision was made to evaluate all the PTS data without regard for presentation rate. Also, because relations between PTS and the increasing energy of the stimulus were being sought, presentation rate did not affect the independent variable. This effectively increased the number of animals at each SEL to 15 except for the 1-impulse exposure conditions. Total sound exposure or exposure level is increased by increasing the peak SPL or the number of impulse presentations.

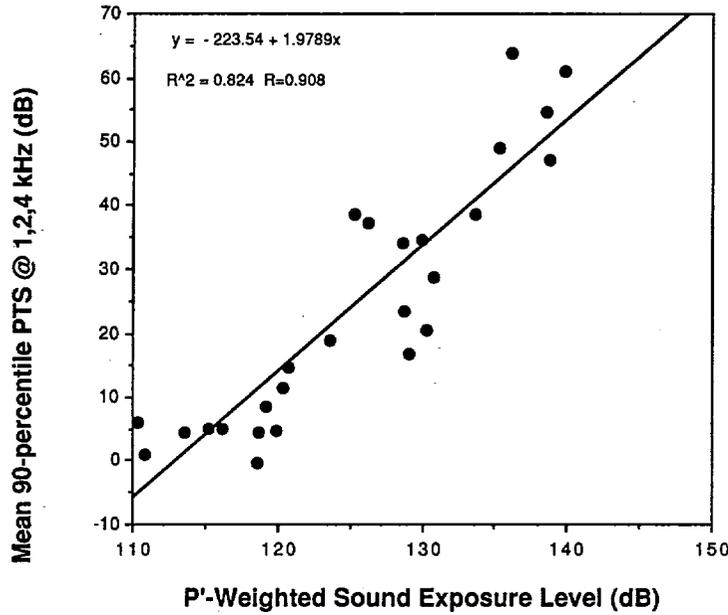
For each audiometric test frequency, the individual animal PTS at that frequency was plotted as a function of the total unweighted SEL in the octave band centered on that test frequency. Two examples of this analysis at 2 kHz and 4 kHz for Source II are shown in Figure 30-10. For impact Sources I, II, and III, 105 individual data points for each source at each audiometric test frequency were plotted over a range of SELs of approximately 30 dB. The actual number of data points in each panel of Figure 30-10 is less than 105, because a number of animals had the same data coordinate. Using data sets such as those shown in Figure 30-10, the 90th percentile hearing loss ( $PTS_{90}$ ) was computed for each SEL at each octave frequency from 0.5 to 16 kHz. The  $PTS_{90}$  at any frequency was computed as follows:

$$PTS_{90} = \bar{x} + st_{.10}$$

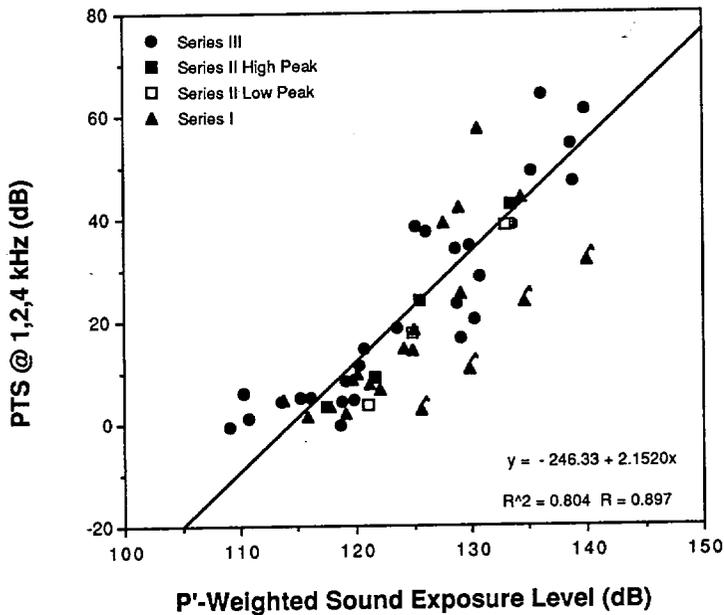
where  $\bar{x}$  is the group mean PTS;  $t_{.10}$  is the value of  $t$  below which 90 percent of the PTS



**Figure 30-10** Two examples that illustrate the individual animal permanent threshold shift (PTS) values at 2 and 4 kHz following the Series III exposures to Source II. The solid symbols represent the 90th percentile values of the PTS at the various exposure energies.



**Figure 30-11** The mean of the 90th percentile permanent threshold shift (PTS) measured at 1, 2, and 4 kHz for all of the groups exposed to the Series III impulses as a function of the P'-weighted sound exposure level. A linear regression analysis (solid line) yields a slope of approximately 2.0 and an X-intercept of 113 dB.



**Figure 30-12** The mean permanent threshold shift (PTS) produced by exposures to the Series I, II, and III impulses as a function of the P'-weighted sound exposure level. The equation for the linear regression line (solid line) is also given.

data lies;  $s$  is the group standard deviation. This procedure yields nine percentile points for each test frequency, shown by the filled symbols in Figure 30-10, i.e., three peak levels for each of three numbers of impacts. This exercise was repeated for each of the six octave test frequencies and for each of the three sources.

From this set of frequency-specific 90th

percentile points, a 90th percentile  $\overline{PTS}_{1,2,4}$  was computed for each exposure group and plotted as a function of the P'-weighted SELs (P'-SELs). These results are shown in Figure 30-11. The P'-weighting has the effect of collapsing all the shock tube data into a reasonably cohesive pattern for which a linear regression produces a relation between  $\overline{PTS}_{1,2,4}$  and P'-SEL whose correlation coefficient is

0.91. A threshold for the onset of  $\overline{PTS}_{1,2,4}$  of 113 dB SEL and a slope of approximately 2 dB  $\overline{PTS}_{1,2,4}$  for each decibel of P'-SEL describes the equation of this regression line.

Figure 30-12 shows the entire data set from the Series I, II, and III exposures plotted as a function of the P'-SEL. As a first approximation the P'-weighting function has the desired effect of unifying the PTS/SEL relation following a diverse series of impulse noise exposures. The correlation coefficient between the PTS and weighted SEL variables is approximately 0.9.

## Conclusion

We have presented a preliminary analysis of a large experimental database obtained from 475 chinchillas that were exposed to a variety of impulse/blast wave noise transients. This analysis, although encouraging in its ability to unify the PTS data, is considered preliminary because only a portion of the data that will eventually be available have been analyzed. In addition to the results presented, the following data sets will ultimately be entered into the database for a final analysis: (1) non-reverberant, high-frequency, Series III-type impulses ( $N = 105$ ); (2) a more detailed exploration of the 1- to 8-kHz region of the empirical weighting function using the Series I narrow-band impulses ( $N = 50$ ); (3) highly-reverberant Series III-type impulses ( $N = 300$ ); and (4) all sensory cell loss data from the above exposures.

The surprising order that is imposed on the PTS data by the P'-weighting function is encouraging and tends to lend some validity to the methods used in the analysis, i.e., the organization of group mean data averaged over several frequencies and, in the Series III exposures, the use of a 90th percentile PTS. The analysis presented would indicate that despite the problems and inconsistencies in some of the data obtained from high-level impulse noise that have been described in the literature, the use of large samples and the systematic variation of exposure conditions can yield a database that reflects some underlying order and can be useful in developing exposure criteria. These data have shown that using electroacoustic methods and narrow-band impulses, a weighting function appropriate for high-level blast waves can be established. This weighting function also may be appropriate for use in the evaluation of industrial impact noise data.

The empirical P'-weighting function presented in Figure 30-7 has a low-frequency segment (i.e., below 1.5 kHz) with a slope of approximately 10 dB per octave, which is greater than the low-frequency slope of either the A-weighting function or the "relative susceptibility" curve presented by Price (1983). This indicates a much smaller hazard from the lower-frequency components of the impulse noise spectrum than previously believed. Above 1.5 kHz the A-weighting function is relatively flat, whereas the Price susceptibility curve rises monotonically at about 18 dB per octave above 3 kHz. The P'-weighting curve provides no evidence relevant to this part of the spectrum. The unusual feature of the empirical P'-weighting function is the 2,450-Hz point. When the weighting indicated by this point is applied to the 2-kHz octave band energy of the impulse of the Series II or Series III data, the effect is to decrease the correlation coefficient between the  $\overline{PTS}_{1,2,4}$  and the P-SEL. (The actual weighting used at the 2-kHz octave band is the value obtained by linear interpolation between the 1,350-Hz and 2,450-Hz data points.) Although the 2,450-Hz point appears to be inconsistent with the rest of the P'-weighting function, it should be noted that this point is the result of a consistent set of data that was obtained from four different exposure groups ( $N = 24$ ). If, however, the P'-weighting function is used—i.e., an attenuation factor of -5 dB is applied to the 2-kHz octave band energy of the Series II and Series III impulses—the correlation coefficient between  $\overline{PTS}_{1,2,4}$  and the weighted exposure level increases to more than 0.9 (see Figures 30-9 and 30-11). This result seems to indicate that the appropriate weighting function to be applied to an impulse spectrum is not a simple monotonic function, as implied by A-weighting or the Price susceptibility curve, but rather a more complex function (at least in the chinchilla) at frequencies above approximately 1 kHz. The data of von Bismarck (1967) on the external ear transfer function and the multifrequency impedance data of Henderson (personal communication), along with the intracochlear pressure measurements of Patterson et al (1988), would indicate that such nonmonotonic behavior is to be expected.

In conclusion, if a suitable weighting function can be established empirically it could then be applied to the spectrum of an impulse to develop an energy-based approach to the establishment of criteria for exposure to a wide variety of noise transients.

## Bases Expérimentales Relatives à l'Estimation des Risques de l'Exposition aux Bruits Impulsionnels

L'analyse des résultats de deux séries expérimentales portant sur l'exposition à deux types de bruits impulsionnels très différents est présentée. Les valeurs sont basées sur des résultats obtenus sur plus de deux cents animaux de laboratoire (chinchillas) chez lesquels les pertes auditives (PTS) et les pertes de cellules sensorielles (SCL) ont été mesurées. Les premières séries d'expositions furent réalisées en utilisant des impulsions réalistes caractéristiques des tirs de trois armes différentes (type Friedlander). Ces impulsions sont produites en utilisant trois sources différentes actionnées à l'air comprimé (tubes à choc). Elles comportent une distribution spectrale d'énergie de large bande avec des pics de bandes d'octave pondérés A situés à 0,25; 1,0; et 2,0 kHz. Les niveaux de crête vont de 150 à 160 dB SPL. Les secondes séries d'impulsions étaient synthétisées par ordinateur à partir de bandes étroites ( $\approx 250$  Hz) reproduites par un haut-parleur de forte puissance. Ces impulsions, dont le niveau crête variait de 124 à 146 dB SPL avaient des fréquences centrales de six valeurs différentes situées entre 0,15 et 3,50 kHz. A partir de chacun des deux groupes de résultats, un niveau lésionnel constant, défini en termes de PTS et de SCL fut mis en relation avec le spectre d'énergie et les niveaux d'exposition globaux de chaque exposition. Les différences et les similitudes trouvées parmi l'ensemble des relations de ce type obtenues avec l'une et l'autre sources d'impulsions ainsi que la valeur prédictive de ces relations sont discutées.

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### References

- Coles RRA, Garinther GR, Rice CG, Hodge DC. Hazardous exposure to impulse noise. *J Acoust Soc Am* 1968; 43:336-343.
- Gold B, Rader CM. Digital processing of signals. New York: McGraw-Hill, 1969.
- Hamernik RP, Ahroon WA, Hsueh KD. The energy spectrum of an impulse: Its relation to hearing loss. *J Acoust Soc Am* 1991; 90 (In press).
- Hamernik RP, Hsueh KD. Impulse noise: Some definitions, physical acoustics and other considerations. *J Acoust Soc Am* 1991; 90 (In press).
- Henderson D, Hamernik RP. Asymptotic threshold shift from impulse noise. In: Hamernik RP, Henderson D, Salvi RJ, eds. *New perspectives on noise-induced hearing loss*. New York: Raven Press, 1982:265.
- Henderson D, Hamernik RP, Salvi RJ, Ahroon WA. Comparison of auditory-evoked potentials and behavioral thresholds in the normal and noise-exposed chinchilla. *Audiology* 1983; 22:172-180.
- Kryter KD, Garinther GR. Auditory effects of acoustic impulses from firearms. *Acta Otolaryngol Suppl* 1965; 211.
- Kryter KD. The effects of noise on man. New York: Academic Press, 1970.
- OSHA, Dept of Labor. Occupational noise exposure. Proposed requirements and procedures. *Federal Register* 1974; 39(207):155-159.
- Patterson JH Jr, Lomba-Gautier IM, Curd DL, Hamernik RP. The effect of impulse intensity and the number of impulses on hearing and cochlear pathology in the chinchilla. USAARL Report No 85-3, 1985.
- Patterson JH Jr, Lomba-Gautier IM, Curd DL, Hamernik RP. The role of peak pressure in determining the auditory hazard of impulse noise. USAARL Report No 86-7, 1986.
- Patterson JH Jr, Hamernik RP, Hargett CE, et al. The hazard of exposure to impulse noise as a function of frequency. USAARL Report 1991 (In press).
- Pfander F, Bongartz H, Brinkmann H, Kietz H. Danger of auditory impairment from impulse noise: A comparative study of the CHABA damage-risk criteria and those of the Federal Republic of Germany. *J Acoust Soc Am* 1980; 67:628-633.
- Price GR. Loss of auditory sensitivity following exposure to spectrally narrow impulses. *J Acoust Soc Am* 1979; 66:456-465.
- Price GR. Relative hazard of weapons impulses. *J Acoust Soc Am* 1983; 73:556-566.
- Price GR. Hazard from intense low-frequency acoustic impulses. *J Acoust Soc Am* 1986; 80:1076-1086.
- Smoorenburg GF. Damage risk criteria for impulse noise. In: Hamernik RP, Henderson D, Salvi RJ, eds. *New perspectives on noise-induced hearing loss*. New York: Raven Press, 1982:471.
- Smoorenburg GF. Effects of Impulse Noise. NATO Document AC/243 (Panel 8/RSG.6) D/9, 1987.
- von Bismarck GV. The sound pressure transformation function from free-field to the eardrum of chinchilla. MS thesis, Massachusetts Institute of Technology, Cambridge, MA, 1967.
- Young RW. On the energy transported with a sound pulse. *J Acoust Soc Am* 1970; 47:441-442.