DAMAGE RISK WITH IMPULSE NOISE EXPOSURE

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Introduction At present there is no single measure, or assessment method, that enables adequate prediction of auditory hazard from impulse noise. Impulse noise is described by many parameters such as peak level, duration, rise- and fall times, impulse energy, inter-impulse interval, impulse rate and the background continuous noise level. This implies that it is very difficult to assess retrospectively the exposure of an individual over periods of years. Thus, it is almost impossible to relate a permanent threshold shift (PTS), measured in a particular individual, to the individual's impulse exposure history. Dose-effect relations, as presented in ISO 1999 for steady noises, cannot be derived for impulse noise. Therefore, ISO 1999 merely indicates that the measured exposure level may be increased by 5 dB when the noise contains impulsive components before applying the dose-effect relations given in ISO 1999 to assess risk of hearing loss. In addition, ISO 1999 indicates that its dose-effect relations should not be applied when the noise contains impulsive components above 140 dB peak level.

TTS-based studies Rather than using PTS data an alternative approach can be based on temporary threshold shifts (TTS) measured shortly after the exposition. In that case the exposition is exactly known. Using TTS as a measure of risk of hearing loss may have some face-value, however, the relation between TTS and the PTS to be expected after repeated exposure to the same noise is not a simple one. The 5-dB-per-factor-of-two-reduction-in-exposure-time rule for intermittent and short-duration steady noises (applied in the USA) resulted from acute TTS experiments whereas the 3 dB rule in ISO 1999 resulted from retrospective PTS analyses. Usually, the TTS studies are based upon TTS measured 2 minutes after the exposure. The relation between the TTS and PTS approach improves when TTS is measured later, for example after 200 minutes (see Passchier-Vermeer, 1973). However, measurable effects after 200 minutes require higher experimental exposure levels, which meet ethical objections. In our recent work, following Pfander (1975, 1980) we have focussed on the TTS approach requiring that the risk of developing permanent hearing loss in the experimental situation should be virtually zero. The data available show that this is most probably true if there is full recovery of TTS within 24 hours. In addition the data available suggest that this criterion is met when TTS within two minutes does not exceed 25 dB.

Summary of TTS studies until 1980 Previously, I have summarized all TTS data available up to about 1980. Sound impulses were produced by sparks, light fire arms, clicker toys, by wood-on-wood or metal-on-metal impacts, and synthetically by loudspeakers, with and without reverberation. The result, presented in Figure 1, showed quite a good correlation between the peak levels on the one hand and the total duration of the impulses on the other hand at which a criterion TTS was reached of 15 dB after two minutes, averaged across TTS at 1, 2, and 3 kHz,

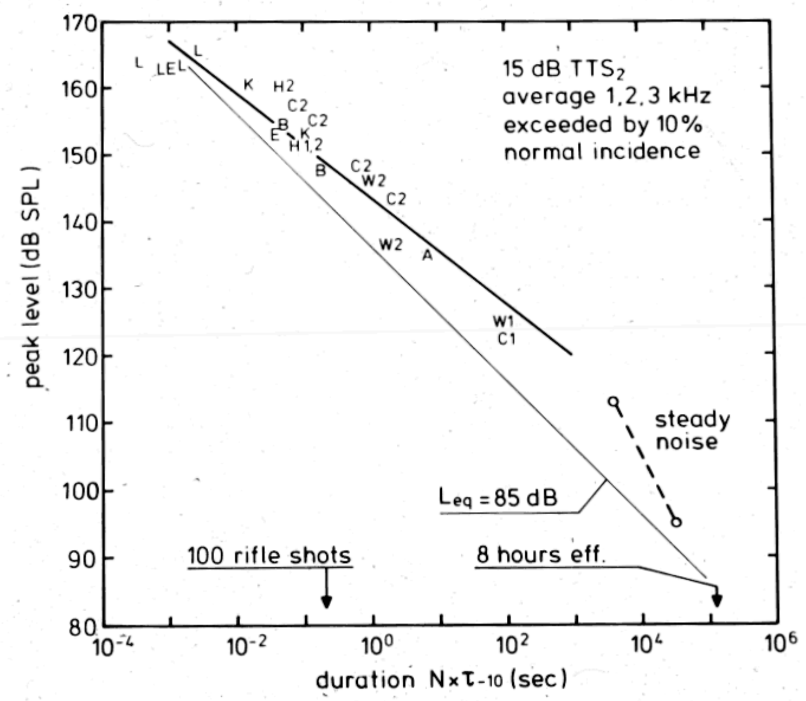

Figure 1. Peak levels as a function of total impulse duration satisfying the criterion of not more than 10% TTS after two minutes in excess of 15 dB, averaged across 1, 2, and 3 kHz.

to be exceeded by (only) 10% of the population exposed and with sound incidence normal to the ear. The criterion of 15 dB, averaged across 1, 2, and 3 kHz, was chosen such that the data available could be compiled without minimal extrapolation. The statistical criterion of 10% excess TTS was based on confidence limits taking into account the (limited) number of subjects in the populations exposed. Total duration was defined as the number of impulses in the exposition multiplied by the duration of one impulse. Impulse duration was taken from impulse onset to the moment in time at which the envelope of the impulse had reached a value of 10 dB below the peak level, τ_{-10}. This measure too was chosen in view of minimizing extrapolations from the measures used in the respective studies. The figure shows that the peak level has to be reduced by 7.8 dB for every 10 dB increase in total impulse duration. This is not quite the 10 dB per factor of 10 increase in duration (or 3 dB per factor of 2) to be expected from the equal energy principle (ISO 1999). In order to harmonize with ISO 1999 the data were approximated conservatively by a line representing an 8-hour equivalent exposure of 85 dB. The outcome of 85 dB suggests that one could use the same exposure limit for impulse and steady noises. However, as one increases the exposure level, TTS grows faster for impulse than for steady noises. Thus, if one would accept an exposure limit of 90 dB equivalent 8-hour level than impulse noise at 90 dB will produce more damage than one accepted for the steady noises at 90 dB. For further details the reader is referred to Smoorenburg (1982, 1992).

Impulses from large caliber weapons and blasts show less TTS After completing the above study it appeared that Fig. 1 predicts more TTS than was actually found for long duration (typically 5 ms) impulses from large caliber weapons and blasts without reverberating components (near ideal Friedlander waves). An early and clear indication was found in the results from animal

experiments published by Dancer *et al*. (1985). They reported a *decrease* in TTS when impulse duration was increased at constant peak level. A systematic analysis for impulses from many large-caliber weapons confirmed that Fig. 1 overestimates human TTS (Smoorenburg, 1992, Chapter 28, Fig. 6). Spectrally, increasing impulse duration implies addition of low-frequency energy while the amount of high-frequency energy remains the same (Fig. 2). Thus, one may try to obtain a better fit between TTS and impulse energy by applying low-frequency filtering, which would reduce the increase in total impulse energy with increasing impulse duration. However, applying A-weighting did not provide a satisfactory result. Even a weighting curve derived from TTS experiments by Plomp *et al.* (1963), which included much more reduction of low-frequency energy, did not yield the correct prediction of TTS. The animal experiment by Dancer *et al*. suggested that no weighting curve, what so ever, could provide a correct prediction when indeed TTS decreases with increasing impulse duration.

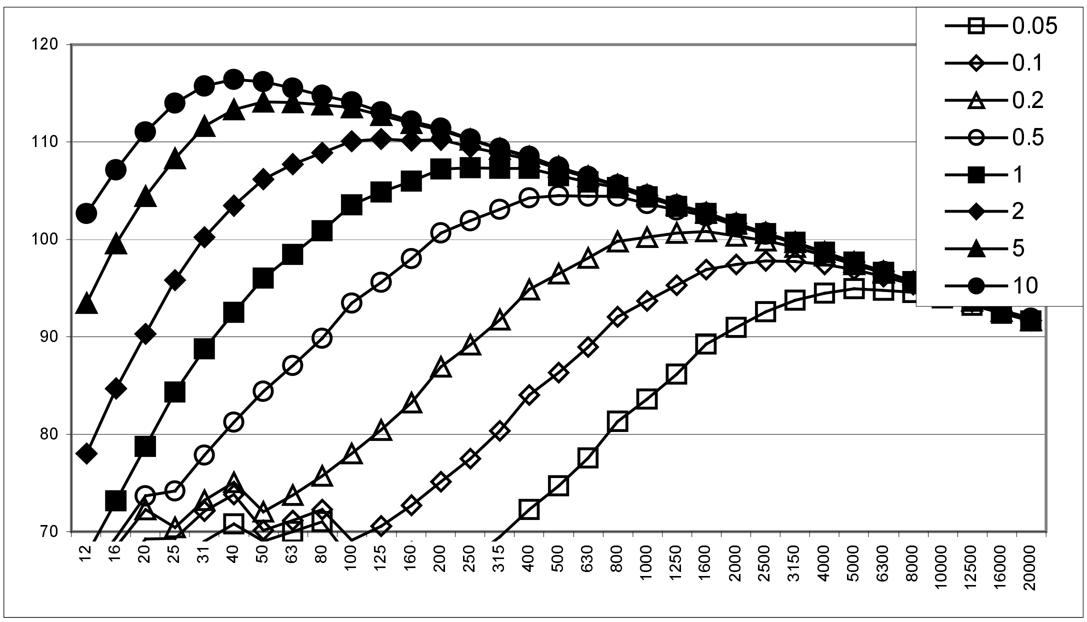

Figure 2. Sound exposure level (SEL) in dB (ordinate) per 1/3-octave frequency band for ideal Friedlander waves. Each curve represents a certain impulse duration (in ms) given in the legend.

New data from the Blast Overpressure Project The results presented above and discussions within NATO Research Study Groups on the effects of impulse noise suggested that new experiments had to be carried out. A large program, called the Blast Overpressure Project, was started in Albuquerque, New Mexico, USA, under supervision of the late Dan Johnson. The program was based on TTS measurements in human volunteers, adopting the criterion of no TTS after 24 hours, described above. Impulse exposures were increased systematically in small steps until a TTS after 2 minutes of 15 dB or over was found. At that point the series of exposures was terminated expecting that the next higher exposure might produce more that 25 dB TTS.

The exposure parameters were peak level, impulse duration and number of impulses. In free field the impulses were near ideal Friedlander waves; peak level varied from 173 to 196 dB SPL; duration from 0.9 to 3 ms, and the number of impulses from 6 to 100. The human subjects used

hearing protection (earmuffs) with all exposures. Impulse sounds were measured under the earmuffs.

The data were analyzed applying the following frequency-dependent weighting functions: linear (no weighting over the frequency range of Figure 2), A-weighting, a weighting according to the threshold of human hearing (T-weighting), and the weighting derived from Plomp *et al.* (1963), which gives the sound energy per frequency band of steady band-filtered noise producing equal TTS (EqTTS weighting). In addition, the analysis was performed without assuming any trade-off function between the number of impulses and exposure level, such as the 3 and 5 dB trade-offs mentioned above in the paragraph on TTS-bases studies. The number factor was included in terms of $\alpha^{10}\log(N)$, α to be optimized. Equal energy corresponds to α=10; a tenfold increase in the number of impulses, N, corresponds to $10\ ^{10}\log(10)$ =10 dB increase in energy. Most variance in the TTS data (almost 80%) could be explained when T-weighting was applied and for $\alpha = 5$. Second best was EqTTS weighting and $\alpha = 7$. The standardized A-weighting explained only 60% of the variance with $\alpha = 3$. Thus, the results clearly indicated that one should apply frequency-dependent weighting which considerably reduces the low-frequency energy in the impulse. Moreover, the results suggest that the number of impulses is less important than equal energy suggests ($\alpha = 10$); let alone the 5 dB trade-off rule which corresponds to $\alpha = 16.6$. Further analysis even showed that TTS for these blasts was virtually independent of impulse number for numbers between 6 and 50. The result strongly suggested that there is a critical sound exposure level. For A-weighting this critical sound exposure level is about 135 dBA,SEL. In terms of equivalent 8-hour levels the exposure should not exceed 98 dBA.

The results for short impulses differ from those for blasts. For these impulses too the data suggest a critical level, in terms of A-weighting 116 dBA,SEL; in terms of the 8-hour equivalent 80 dBA (5 dB lower than in Fig. 1 because of the new TTS criterion). Thus, in terms of a frequency-dependent weighting and a number rule we do not find one dose-effect relation for all kinds of impulses. This result is related to Dancer's finding quoted above: the increase in low-frequency energy with increasing impulse duration seems to have a protective effect. Price and Kalb (1991) have proposed a model based on nonlinear sound processing by the ear which could account for this effect. However, subjecting the present data to his model did not yield a good fit. Price's model seems promising but the present data suggest that its parameters have to be adjusted.

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