Assessment of Impulse Noise regarding Harmfulness to Hearing

Beat W. Hohmann
Physics section, Swiss National Accident Insurance Fund Suva, CH-6002 Lucerne, Switzerland.

Summary

For prevention or for compensation cases, a simple assessment of intensive impulse noise is needed. In order to choose the most appropriate frequency weighting, the transfer function from the free sound field (where we measure) to the inner ear (where damage occurs) must be taken into account. Regarding the most appropriate time constant, the reaction of the inner ear is the reference, and many results indicate that it is not the peak level (rise time 50 microseconds), but rather the short-term sound energy that is correlated with permanent hearing damage.

In Switzerland, a sound exposure level L_E of 120/125 dB(A) is used as a criterion for damage risk since many years. For very high sound levels (> 170 dB, e.g. heavy weapons), AHAAH should be used which is able to simulate the nonlinear behavior of the hearing system.

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0. Introduction

The assessment of intense impulse noise as a risk to hearing is discussed since many decades. With early instrumentation, the correct measurement (peak level, dynamic range, rise time, slew rate, short-time-energy integration) was a severe problem. Nowadays there are no longer such technical limitations, but finding the best possible approximation for the reaction of the human ear when exposed to impulse noise is the challenge.

1. Frequency weighting

1.1. Fundamental considerations

Where the harmfulness of excessive noise exposure for the hearing is concerned, sensations do not play a role: music considered to be pleasing can cause the same hearing damage as annoying industrial noise at work. Here, it is a question of which frequency-dependent effects or deformations a sound signal from the free sound field (where we set up our measurement microphone) to the inner ear (where the damage finally takes place) is subject to. We are therefore looking for the transfer function from the free sound field, with the influence of the head (reflection or shadow) via the external and middle ear through to the inner ear (Figure 1).

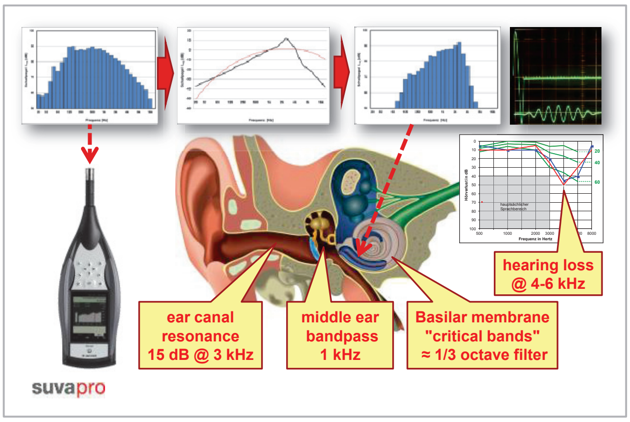

Figure 1. From the free sound field to the inner ear.

From this perspective, the oft-heard argument that the C-filter must be used for the assessment of harmfulness for the hearing because of the equal loudness contours for high SPLs represents a fundamental misunderstanding.

1.2. Relative harmfulness of low and high frequencies for the hearing

Already in 1972, H.E. von Gierke and C. W. Nixon [1] reported that Sonic Booms of 170 dB (Peak, unweighted) did not have any detrimental – neither temporary nor permanent – effect on hearing. These booms had a rise time of 5 ms and a duration of 20 ms, and predominantly low-

frequency content.
On the other hand, the evaluation of 600 cases of NIHL due to noise from weapons [2] in the Swiss army showed that a single shot of the Swiss standard assault rifle (Stgw 57, rise time a few microseconds, peak level 168 dB, effective duration about 1 millisecond) can cause permanent hearing damage, probably due to the predominantly high frequency spectrum. This indicates that for human hearing high frequencies are much more critical than low frequencies.

The studies carried out by Dr. Armand Dancer at the German-French Institute in St. Louis made it clear that low frequencies, for example those of heavy weapons, for a given (unweighted) sound pressure level are less harmful than higher frequencies in the range of 1 to 6 kHz. Therefore even at very high sound levels well above 140 dB, the weighting filter A is suitable for the assessment of harmfulness for the hearing [3].

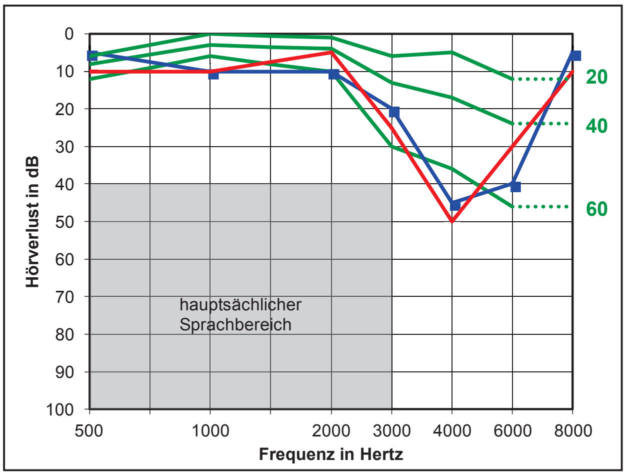

Figure 2. Audiogramme, noise-induced hearing loss.

Another indication of the relative harmfulness of low and high frequencies to the ear can be seen in the fact that hearing loss almost always appears first in the 4 to 6 kHz range and that in the further progression, too, the dip in the audiogram is most pronounced there (red and blue curve).

1.3. Recommendations of NATO study group

According to report NATO RTO TR-017 HFM-022 [4], "the analysis shows that a frequency weighting function putting more emphasis on the contribution from high-frequency energy to the exposure measure will improve the accuracy of auditory hazard prediction. The 19-dB difference between exposure limits for rifles and blasts when applying A-weighting decreases to about 13 dB when a weighting function is applied that follows the threshold of human hearing (MAF in figure 3). It decreases to about 10 dB when the weighting function is based on bands of noise producing the same TTS."

1.4. Equal hazard contour

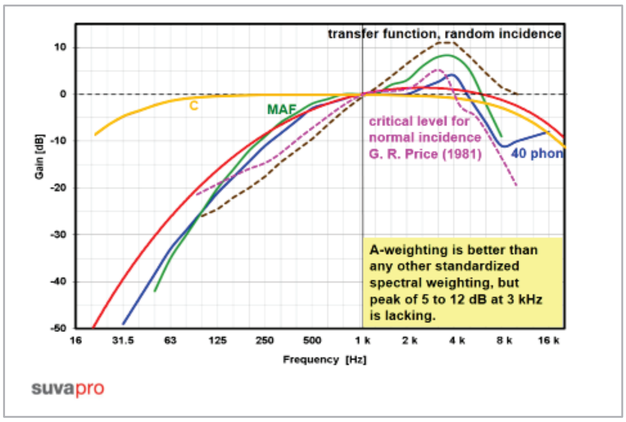

Figure 3. From the free sound field to the inner ear.

Figure 3 compares several approaches to an equal hazard contour, including the critical level contour [5]. Despite some deviations they have in common that they are much closer to A-weighting than to C-weighting, that the attenuation at lower frequencies is equal or greater than provided by A weighting and that they show some amplification in the frequency range between 1 kHz and 6 kHz.

1.5. Limitations of A-weighting

Under certain conditions, low frequencies are not just less harmful but may even have a protective effect, as the middle ear excursion reaches its limit and the transmission of high frequencies to the inner ear is reduced. This could explain why the deployment of airbags does not always cause permanent hearing damage, despite the very high sound levels of 160 dB Peak and the A-weighted sound energy that is equal to a gunshot at the ear of the rifleman. Such a non-linearity cannot be simulated by conventional frequency weighting.

1.6. Spectral analysis

At least above 500 Hz, the basilar membrane has some analogies with spectral analysis in 1/3 octave bands: The bandwidth of the critical bands is always about 20 % of the central frequency. As mechanical filters and electrical filters are principally equivalent, we can suppose that also the temporal behavior is similar, i.e. that the step response consists of some oscillations of the central frequency (figure 4).

Figure 4. Input signal (above) and response of 1/3 octave filter (below).

Even if this response takes more time than the duration of the input signal itself, no energy is lost, and after integration over a sufficiently long time exceeding about 10 periods of the lowest frequency to be considered, the spectral content is correctly reflected in the equivalent level (L_{eq} or L_{AE}) per band. Therefore, analysis in 1/3 octave bands, pre-weighted with the transfer function from the free sound field to the inner ear (figure 3, at least A-weighting), shows the spectral repartition of the load onto the basilar membrane. For a broad range of input spectra, the maximum load will always be at 2 to 4 kHz which explains the typical audiogram with a dip at 4 or 6 kHz after overstimulation.

2. Time weighting

2.1 L_E and damage risk

Already in 1970, experts agreed that is it not the peak level alone that causes the damage, because an extremely short impulse will not lead to any deflection of the basilar membrane. But at that time, integration of the sound energy was not yet possible. Therefore, various definitions of impulse duration were defined, for example the Pfander duration (figure 5), with the intention to approximate the energy content of the signal using peak level and duration.

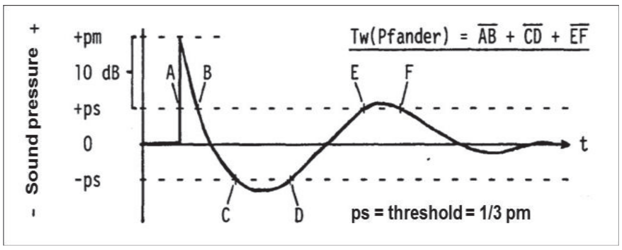

Figure 5. Definition of Pfander duration.

Unfortunately, this intention got forgotten when digital instruments were able to integrate the sound energy even for very short impulses and to calculate L_{eq} or L_E.

Out of 600 cases of hearing damage of the Swiss Army, in 183 cases the sound exposure L_{AE} on one hand (knowing the weapon, the distance, the acoustic environment and the number of impulses) and the permanent hearing loss on the other hand (corporate hearing loss according to CPT-AMA, modified by Suva, from the auduiogram) could be determined with sufficient precision [2]. The result of the analysis is to be seen in figure 6.

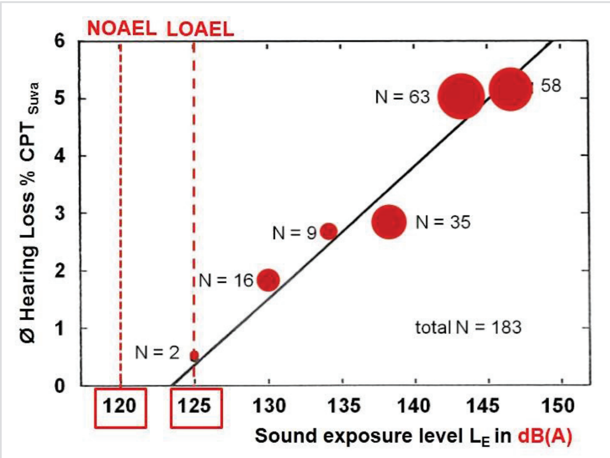

Figure 6. Sound exposure and hearing loss of 183 cases of hearing loss compensated by Swiss army insurance.

The analysis shows that with increasing L_{AE}, the average permanent hearing loss as well as the number of observed cases increases. In other words: Above 125 dB L_{AE}, the risk (probability) and the expected severeness (hearing loss) increases. 120 dB L_{AE} could be seen as a “no observable adverse effect level” NOAEL, and 125 dB L_{AE} as a “lowest observed adverse effect level” LOAEL.

For prevention of permanent hearing loss, 120 dB L_{AE} is a reasonable criterion.

The number of impulses is taken into acount proportional to energy. This can be done during the measurement (letting run the sound level meter for the whole series of impulses) or by calculation (e.g. 2 impulses = + 3 dB).

3. Comparison with other criteria

3.1 Suva criterion and VDI criterion

For insurance (compensation) cases, the VDI criterion of 135 dB L_{AI} is still used in Germany. As just the maximum level is considered, the number of impulses is not taken into account. The relation between Suva's criterion and the VDI criterion therefore depends on the number of impulses: For a single impulse, the VDI criterion is equivalent to 120 dB L_{AE}. For 3 identical impulses, the VDI criterion is equivalent to 125 dB L_{AE}. We could conclude that there is some difference, but no contradiction between both criteria.

3.2 L_{AE} and Auditory Hazard Assessment

It is obvious that a mathematical model of the ear [6] can provide a much better approximation of the human ear than just combining the most appropriate frequency weighting and the best possible time weighting. Therefore, a comparison of the two criteria for different kinds of real impulses is interesting. As L_{AE} is a logarithmic value, the auditory risk units or ARUs shall also be displayed on a logarithmic scale in order to check if there is a correlation between the two methods.
This is what David Pazen from the ENT Department of the University Hospital Cologne did for impulses of different levels, spectra and durations [7]. The result appears in figure 7 (ARUs shown are for a warned subject):

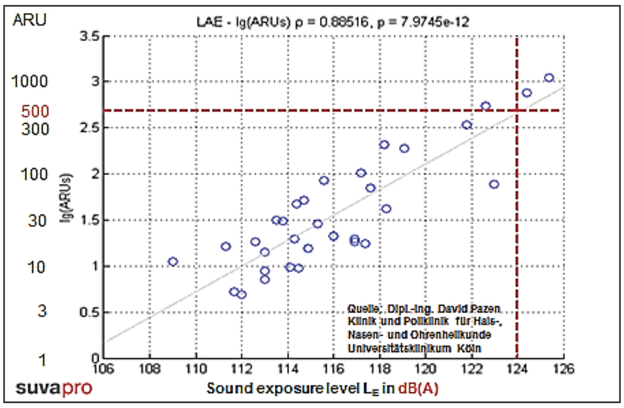

Figure 7. L_{AE} and ARUs for different impulses.

Besides the visible correlation, it is interesting to note that the criterion of 500 ARUs is equivalent to about 124 dB L_{AE} and therefore close to the proposed damage risk criterion of 125 dB L_{AE}.
But this correlation disappears completely if unweighted instead of A-weighted L_E is considered. This is not surprising as the ear model is also based on the transfer function from the free sound field to the inner ear.

In the Auditory Hazard assessment algorithm for Humans AHAAH, the ARUs of multiple impulses are simply added. This is equivalent to the energy-equivalent integration of multiple impulses in the L_{AE} (by direct integration during measurement or by calculation, see above).

4. Conclusions

We see clear evidence that, also for very high sound levels, A-weighting is the most appropriate of the standardised weighting curves. As the energy content of the impulse is the most important parameter for damage risk, L_E is the logical choice for time weighting and also solves the problem of the addition of multiple impulses in a simple and unambiguous way.

On a whole, Suva's L_E criterion is as close to the physiology of human hearing as possible with conventional standardised measuring technique and correlates quite well with AHAAH up to peak levels of 170 dB. It is therefore suitable as a simple method for the assessment of gunshots, airbag deployments and other short-time high-level sound events. Even if the protecting effect of very intense low frequencies is neglected, Suva's method for impulse noise assessment remains conservative, i.e. it stays on the safe side.

On the other hand, the C-weighted peak level used in the EU Directive on Noise at Work has nothing to do with hearing physiology and damage risk, neither in the frequency domain nor in the time domain.

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