Threshold shifts and restitution of the hearing after energy-equivalent noise exposures with an equal NRC-value and non-equal frequency composition

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ABSTRACT

Based on industrial noise, test noise exposures were configured that were completely comparable in the sense that they all had a mean level of 94 dB(A) for 1 h and a Noise Rating Curve-value of 92, but for two of them, the band levels were increased in the lower frequency range and in the higher frequency range of the industrial noise, respectively, with compensating attenuation in the other frequency ranges. Ten otologically normal test subjects were exposed to the 3 noises which followed a change-over test design on 3 days. The maximum threshold shift TTS_2 and the time needed for a complete recovery of the hearing, associated with the accented high-frequency noise were substantially higher and lasted longer than with the unaltered original industrial noise. The accented low-frequency noise also resulted in substantially higher threshold shifts that persisted for a longer time than those of the unaltered noise exposure. As a result, the Integrated Restitution Temporary Threshold Shifts (IRTTS), known as measure for the “Physiological Costs” in their entirety that the hearing must “pay” for the preceding noise exposures, differend very distinctly. Finally, when the IRTTS-values of the two test series with the altered spectra are expressed relative to the value for the original industrial noise, the quotients of 5.26 and 1.99 indicate substantially higher physiological responses associated with accented high-frequency and low-frequency components in energetically identical noise exposures.

1 INTRODUCTION AND MOTIVATION OF THE STUDY

In the rating of noise exposures, very simple and easily manageable methods that are based on so-called single number values are typically used (referring to their problematic use see, e.g., Strasser 2005; Strasser & Irle 2006) instead of measures that attempt to do the hearing’s complexity justice such as binaural loudness measurements or psycho-acoustic methods (cp. Zwicker & Fastl 1990; Genuit 2005). Particularly common is the daily noise exposure level $L_{Ex/8\ h}$ (the former rating level L_{Ard}), an energy-equivalent mean value that is related to an 8-hour day (NN 2007a) that is calculated from noise of different level and duration via a formula (cp. Fig. 1).

For instance, a daily noise exposure level of 85 dB for 8 h, due to the 3-dB exchange rate, can be built by 88 dB for 4 h, 91 dB for 2 h, or also energy-equivalent 94 dB for 1 h (cp. left part of Fig. 1). The use of the A-filter pretends to represent at least an attempt to relate the frequency weighting of the noise to the characteristics of the hearing. The daily mean noise dose, however, that is expressed in such a fashion fails to consider whether quiet spells occur in between the individual noise exposures – which would be advantageous to the hearing – or whether those important resting phases are filled up with additional noise. While such noise may be energetically insignificant, is still hinders the hearing’s restitution after threshold shifts that were caused by preceding high noise exposures (see Irle et al. 1998). Indeed, according to the right part of Fig. 1, it is energetically irrelevant, whether a daily noise exposure of

85 dB(A) stems from a noise level of 94 dB(A) for 1 h and a silent period for 7 h, or whether these 7 h are filled up with noise of 75 dB(A). In addition to the offsetting to noise exposures of varying duration and loudness, the inadequate dose maxim – with respect to the effects of noise on the hearing – is also applied in the rating of noise exposures with different frequencies. That is, the 3-dB exchange rate is not only applied to the time dimension, but also to the frequency. In the latter case, the filling up of frequency bands up to a certain degree is once again possible without a resulting change in the rating level even in the decimal places. Similarly, the use of Noise Criterion and Noise Rating Curves (NC, NRC) for the frequency weighting and, ultimately, for the rating of stationary noise, i.e., noise that is constant over time, does not appear to be appropriate to address the problem sufficiently.

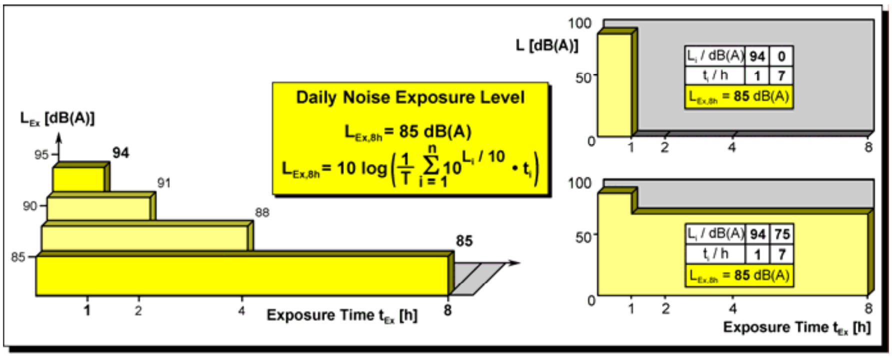

Figure 1: Sound pressure levels of different duration leading to an equal daily noise exposure level (in this case $L_{Ex,\,8\,h}$ = 85 dB(A), using the “3-dB exchange rate”)

Since Noise Rating Curves look like the equal-loudness contours (NN 1987), it can be assumed that they would have been established based on profound psycho-physiological responses. Engineers, very often, appreciate Noise Rating Curves because they believe in these criteria giving direction to a highly qualified assessment of annoyance and speech intelligibility as well as to a general rating of noise (cp., e.g., Schmidt 1988). In a serious evaluation, however, they are both problematic and curious. No matter, an octave-band level analysis of the sound exposure is carried out but thereafter, the valuable information about the spectral distribution of the exposure is overruled completely in order to create a single number rating value which is determined solely by one frequency band level. Despite the fact, that ISO R 1996 (NN 1971), dealing with NRC, has been withdrawn already, Noise Rating Curves, however, still exist in guidelines (NN 2000), in textbooks (NN 1991a; Schmidt 1988), as well as in the scientific literature (e.g., Broner 2005).

As can be seen in Fig. 2, similar to the curves of perceived (subjective) loudness, with the 1 kHz octave band as reference point, the Noise Rating Curves permit higher levels at lower frequencies and dictate lower levels at higher frequencies. Rather than only forming a single number parameter with the A-filter, this method at least includes an octave-level analysis of the noise, which is followed by a comparison of the results with the Noise Rating Curves. Details on Noise Criterion Curves, published first by Beranek (1957), the replaced NCB (Balanced Noise Criterion Curves) and Noise Rating Curves see amongst others Beranek (1988), Kosten & Van Os (1962), NN (1989) and Schaefer (1984).

For example, the noise spectrum shown in the left part of Fig. 2 is characterized with a NRC value of 80. However, since ultimately only the octave level that is tangent to the highest NR curve is used as the relevant single number parameter (and the noise is then characterized with this value), even a far-reaching “filling up” of all other frequency bands with noise energy would be permissible without any resulting change in the NRC-value. That is the case – as shown in the middle of Fig. 2 – with increased levels in the lower frequency bands as well as with increased levels in the higher frequency bands (see right part of Fig. 2). A significantly broader spectrum, however, will presumably have a different effect on the hearing and the annoyance as well as speech interference than the concentration of noise on a small number of frequency bands. The filling up of the frequency spectrum is possible without consequences for the NRC-value. But is the filling up also possible without any impact on the hearing? To what extent can such a method, used for prognosticating the effects of noise, actually make sense?

Thus, the objective of the study was to quantify the effects of noise exposures that are energetically equivalent, but differ in their frequency composition via sound-audiometrical measurements of hearing threshold shifts. It was important that other factors that have the potential to modulate the threshold shifts such as especially the time structure and the semantic meaning of noise were kept constant.

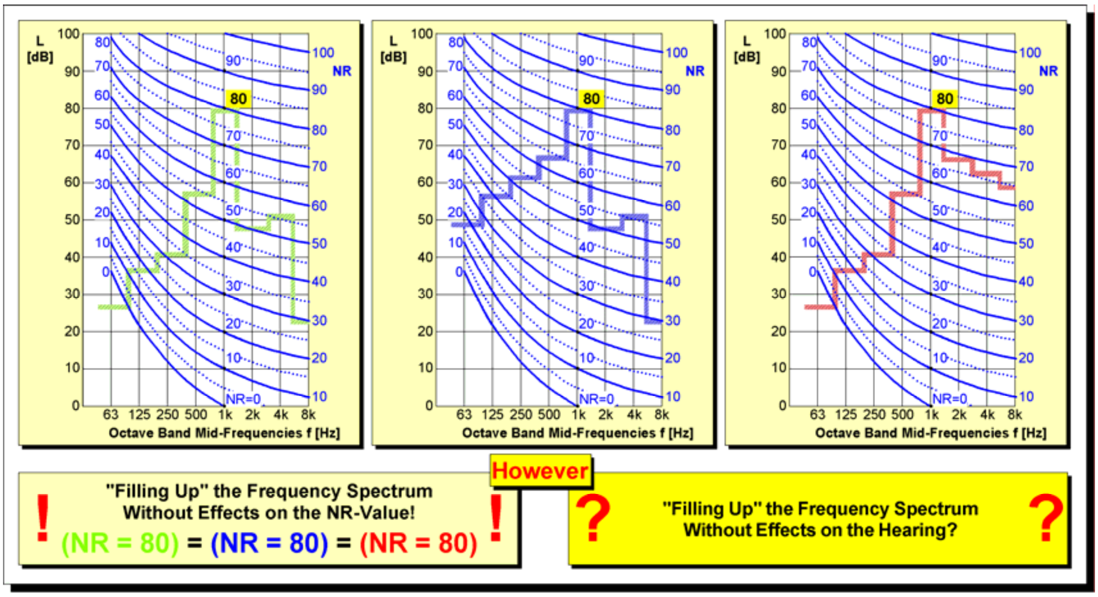

Figure 2: Noise rating curves (NRC) according to ISO R 1996 with various octave-level spectra

2 METHODS

2.1 Configuration of the energy-equivalent test noise exposures with an equal NRC-value and test design

Thus, test noise exposures (94 dB(A)/1 h) were configured based on an industrial noise, that were completely comparable in the sense that for two of the test series, the level was increased in the higher frequency range and in the lower frequency range of the industrial noise, respectively, with compensating attenuation in the other frequency ranges. The unaltered noise (with respect to the frequency) was used as reference acoustic exposure.

The middle row in the upper part of Fig. 3, first of all, contents the octave-band sound pressure levels of the original industrial noise (0) which was provided for the exposure in Test Series I (TS I). The most commonly used A-weighting network delivered an overall, all-inclusive band level of 94 dB(A). As expected, C-weighting or also the unweighted (linear) band levels led to slightly higher overall levels

(96.6 dB(C) and 96.8 dB_{lin}, respectively). For an other Test Series (TS II) a deliberately low-frequency accentuated exposure was used (indicated by L in Fig. 3). For this reason, i.e., the octave bands around 63 and 125 Hz of the original noise were amplified by 11 and 14 dB. Due to the strong negative relative response (attenuation) of the A-weighting network, the dB(A)-value of the exposure remained unchanged despite only small level reductions in the higher frequency bands occurred. For the accented high-frequency noise in TS III (cp. H in Fig. 3) the band levels in the higher frequency range, e.g., the octave-band level around 8 kHz had been increased by 10.8 dB while very limited compensating level reductions in the lower frequency range took place. As can be seen by rating the three spectra by the NR curves, all three exposures with an energy-equivalent mean level of 94 dB(A) and a dominant level of 94 dB, each, in the octave around 500 Hz, are identical also with respect to the NRC-value of 92.

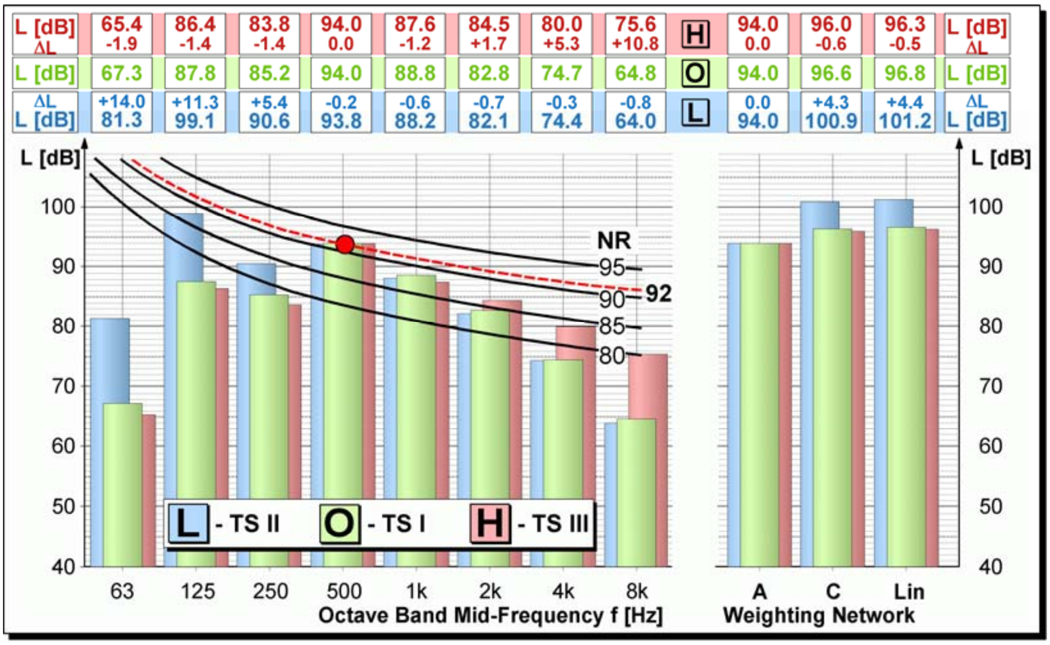

Figure 3: Octave-band pressure levels of the test exposures and level differences of the low- and high-frequency accentuated noises as well as A-weighted, C-weighted, and linear levels with NR-curves

The physiological responses to the exposures (94 dB(A)/1 h, each) were expected to depend on the preceding type of exposure. This should be true for the maximum temporary threshold shifts which can be measured in the form of TTS_2-values immediately after the exposure. Similarly, the restitution, especially the restitution time t(0 dB), i.e., the time duration until the threshold shifts have completely subsided, was expected to be also a function of the preceding exposure in TS I through TS III. The exposures were played on a CD player and were transmitted via an amplifier to (two) loudspeakers in a soundproof cabin. Simultaneously, a nominal value adjustment was provided. The test subject was sitting in the cabin in a standardized position, whereby the resting hearing threshold (prior to the exposure) was measured, and the restitution time course (after the exposure) until the resting threshold was reached again were audiometrically determined.

2.2 Subjects and audiometric procedures

In a cross-over test design, 10 test subjects (Ss) were exposed to the three noises in randomized order on different days, thus acting as their own control. All (5 male and 5 female young) subjects (in the age of 21 to 24 years) were individuals with no previous damage to the haring. They had been selected as otologically normal Ss according to DIN ISO 4869-1 (NN 1991b).

The individual resting hearing threshold, which was determined before every test, served as a basis for subsequent measurements and analyses. After the sound exposure, the individual hearing threshold shift was quantified via multiple measurements, whereby the frequency of a test subject's maximum threshold shift TTS_2 had to be determined within the first 2 min. With this frequency of the maximum threshold shift (normally 4 kHz), also the hearing threshold shift's restitution was measured. The individual restitution time course TTS(t) was determined, starting with the measurement of TTS_2. The last audiometric measurement occurred at t(0 dB), i.e. the time needed for a complete recovery of the hearing.

The shape of the restitution time course resembles a decreasing exponential function, when a linear time scale is used. If, however, it is plotted against a logarithmic time scale the regression function TTS(t) is a straight line. Details on quantifying hearing threshold shifts associated with sound exposures and depicting audiometric parameters such as $TTS_{2\ reg.}$, $t(0dB)_{reg.}$ and IRTTS (Integrated Restitution Temporary Threshold Shifts) by regression-analytical analyses see Irle & Strasser (2005).

3 RESULTS

Fig. 4 summarizes the audiometric responses to the various energy-equivalent noise exposures. For TS I, i.e., the original noise exposure, regression-analytically determined characteristic values $TTS_{2\ reg.}$ of 8.7 dB (at the beginning) and $t(0\ dB)_{reg}$ of 43 min (at the end of the "smoothed" restitution course) lead to overall physiological costs IRTTS of 99 dBmin. For the low-frequency accentuated exposure in TS II, the characteristic values were 11.6 dB, 70 min, and 197 dBmin. The high-frequency accentuated industrial noise in TS III was associated with 16.3 dB, 148 min, and finally, an IRTTS-value of 521 dBmin, which represents a multiple of the total physiological costs of the other exposures. According to the two-tailed WILCOXON-test, the differences in the maximum temporary threshold shifts are significant. Similar is true for the restitution times, and for the IRTTS-values.

When the IRTTS-values of the two test series with the altered spectrum are expressed relative to the value for the original industrial noise in TS I, the quotient 197 dBmin/99 dBmin = 1.99 indicates already a doubling of the physiological costs, which the hearing has to pay for intensive low-frequency components in the noise exposure. The exposure to accented high-frequency components even resulted in a value of 5.26 (521 dBmin/99 dBmin) and thus "physiological costs" that were more than 5 times as high as after the exposure to the original noise.

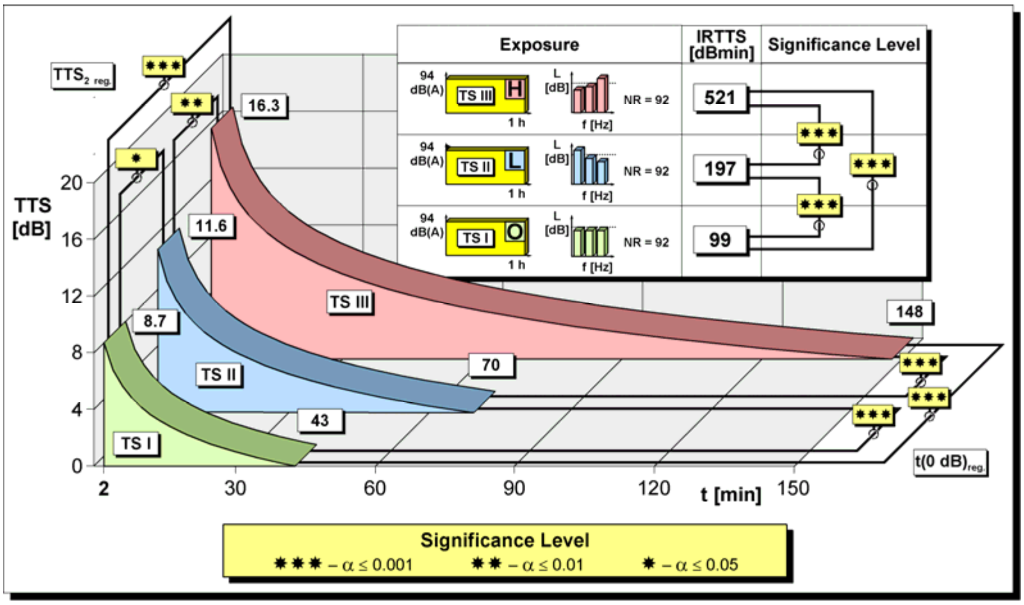

Figure 4: Restitution time courses TTS(t) of various energy-equivalent noise exposures with characteristic values $TTS_{2\ reg.}$, $t(0\ dB)_{reg.}$, and physiological costs IRTTS as well as symbolic labelling of the significance level of differences between the test series (According to the two-tailed ILCOXON-Test)

4 DISCUSSION

The study showed that the physiological costs that the hearing must pay for three energetically identical noises which had a mean level of 94 dB(A) for 1 h, but varied in their frequency components, are distinctly different. This is true even if these components are of no relevance for the NRC-value, since the energy that they contain is largely attenuated by the A-filter, and since the two spectra are irrelevant for the rating by the NRC, respectively.

a) Effects of the accented high-frequency noise

From a psycho-physiological viewpoint, it seems to be plausible that sharpness of an especially high-frequency accentuated noise can play a dominant role both in subjective assessments of the exposure, e.g., annoyance and in physiological processes in the inner ear. Therefore, it can be expected, that especially noise energy concentration on smaller areas of the basilar membrane is also reflected by increased temporary threshold shifts.

According to the standard DIN 54 692 (NN 2007b), equally high overall sound pressure levels of narrow-band noise (e.g., 60 dB with a mid-frequency of 1 kHz and a bandwidth of 160 Hz), of wide-band noise (with an upper cut-off frequency of 15 500 Hz) and of high-pass noise (with cut-off frequencies of 3 150 Hz and 15 500 Hz) cause highly varying hearing sensations. In deed, sharpness S increases substantially (from 1.00 acum through 1.98 acum to 3.64 acum). Furthermore, an increase of the mid-frequency of a narrow-band sound exposure and an increase of the lower cut-off frequency of a wide-band noise is associated with a substantial increase of sharpness. Details on definition and dependency of sharpness of sound exposures see, e.g., von Bismarck (1971), Fastl (1993) and Widmann (1993).

The extent of the experimental findings of this study, however, namely 5 times higher IRTTS-values associated with the accented high-frequency exposure, related to the original noise, is surprising only at a first glance. It may be interpreted as the result of an obviously high susceptibility and a strong response of the subjects to the unnatural “sharp” acoustic load. Apparently this experience was not limited to the psychological domain but also had an impact on physiological correlates.

Furthermore, the distinct characteristics of the exposure with respect to the frequency distribution and energy content – which will be explained in the following – may play a role for the effects on the hearing. The increase of the octave-band levels around 4 and 8 kHz (from 74.7 and 64.8 dB in the original noise) by 5.3 and even 10.8 dB (to 80.0 and 75.6 dB) (cp. upper part of Fig. 3), remarkably did alter neither the A- or C-weighted nor the unweighted (linear) all-inclusive level. Using the A-weighting network intentionally led to identical 94 dB(A) for all exposures. When using the C-weighting or the linear network, (with 96.0 dB(C) and 96.3 dB_{lin}) the accented high-frequency exposure appeared to be even slightly lower than the original noise which exhibits levels of 96.6 dB(C) and 96.8 dB_{lin}.

This strange result is due to the fact that for the original and the accented high-frequency noise, the band levels of the two upper octaves related to the band levels for the octaves between 125 Hz and 1 kHz, especially the dominant level of 94 dB for the octave around 500 Hz, are absolutely negligible in terms of energy (of the exposure). With 87.8, 85.2, 94.0, and 88.8 dB compared to 74.7 and 64.8 dB the band level differences in the original noise amount to much more than 10 dB. Thus, the lower levels, not at all, can contribute to the overall-inclusive level. Almost similar is true for the altered noise despite its high-frequency accentuation. Even the rather high levels of 80.0 and 75.6 dB in addition to 86.4, 83.8, 94.0 and 87.6 dB are energetically absolutely irrelevant. But this, not at all, does mean that energy inherent in the band levels does not exist for the hearing.

As shown already in prior studies [6], energetically negligible noise of 70 dB(A) for 3 h in addition to preceding 94 dB(A)/1 h increased IRTTS substantially by the factor of 2.44. What happens for the hearing when, e.g., resting phases in between high noise exposures are filled up by noise with levels which remain more than 10 dB below the peak levels (cp. Strasser 2005), can also be expected at least hypothetically for the filling up of frequency bands in noise exposures. As shown by Strasser et al. (2007), a narrow-band sound exposure in the higher frequency range (an octave-band level of 94 dB(A)/1 h around the mid-frequency of 2 kHz) also caused significantly higher IRTTS values than an energy-equivalent wide-band sound exposure (overall level of 94 dB(A)/1 h of 4 band levels with the mid-frequencies 250 Hz, 500 Hz, 1 kHz and 2 kHz). Compared to an extremely low-frequency narrow-band noise (octave-band level of 94 dB(A)/1 h around 250 Hz) the physiological costs to the hearing were even 5 times higher.

b) Effects of the accented low-frequency noise

Also irritating, at a first glance, are the effects of increased band levels in the lower frequency range. The IRTTS-values that were almost two times as high as after the exposure to the unaltered original noise, however, can be explained by a substantially higher load of the hearing due to the filling up of band levels in the low-frequency range. An increase, e.g., of 11 or even 14 dB in the two lowest octave bands was almost completely levelled off by the relative response of the A-weighting network. This, oftentimes, leads to an underestimation of the effects of low-frequency noise (cp., e.g., Berglund & Hassmen 1996; Genuit 2007; Leventhall 2003). When using the C-weighting network which normally should be applied for frequency weighting of sound levels between 90 and 120 dB, the accented low-frequency noise exhibits a substantially higher acoustic load than the unaltered noise. Its overall level of 100.0 dB(C) exceeds the 96.6 dB(C) of the original noise level by more than 3 dB.

It should not come as a surprise if an increase of this extent is also associated with a doubling of the physiological costs ($IRTTS_{TS\ II}/IRTTS_{TS\ I}$ = 1.99) for the hearing.

5 CONCLUDING REMARKS

The experimental results discussed above raise serious questions about the use of conventional measures that give exactly identical ratings to the examined real-life acoustic exposures using the concept of energy-equivalence, the A-weighting network, and Noise Rating Curves. From the quite different short-term reversible responses of the hearing to the exposures with a limited mean level of 94 dB(A)/1 h which was due to ethical reasons, an also quite different long-term hearing risk can be prognosticated when unnatural exposures are repeatedly higher in the "rough" industrial working world.

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