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### Abstract

This review concentrates on the effects of low frequency noise (LFN) up to 100 Hz on selected physiological parameters, subjective complaints and performance. The results of laboratory experiments and field studies are discussed in relation to the thresholds of hearing, of vibrotactile sensation and of aural pain. The effects of LFN may be mediated through different ways. Temporary or permanent hearing threshold shifts seem to be due to acoustic stimuli above the individual hearing threshold. However, non-aural physiological and psychological effects may be caused by levels of low frequency noise below the individual hearing threshold. The dynamic range between the thresholds of hearing and of aural pain diminishes with decreasing frequency. This should be taken into account by the setting of limits concerning the health risks. Sufficient safety margins are recommended. The use of a frequency weighting with an attenuation of the low frequencies (e.g. G-weighting) does not seem to be appropriate for the evaluation of the health risks caused by LFN up to 100 Hz. It may be proposed to measure third octave band spectra or narrow band spectra. A comparison with the known human responses caused by the measured levels and frequencies could help to evaluate the health risks. Some proposals for further investigations were given: (1) experimental methods to discover the ways mediating the effects of low frequency noise, (2) consideration of the individual hearing threshold or hearing threshold shift and of the vibrotactile threshold in the low frequency range to be able to judge the effects, (3) consideration of combined body vibration caused by airborne low frequency noise or by other sources, (4) modelling to analyse the transmission of the acoustic energy from the input into the body to the structures containing sensors, (5) consideration of probable risk groups like children or pregnant women.

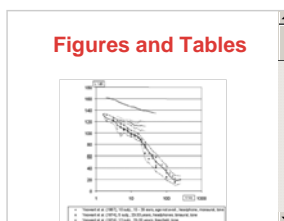
**Keywords:** *infrasound, hearing threshold, vibrotactile perception, aural effect, non-aural effect, complaint, performance*

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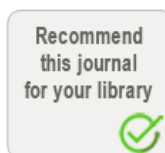
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### Introduction

Although some comprehensive reviews have been published in the past decades (Westin 1975, Harris et al. 1976, Tempest 1976, Broner 1978, Johnson 1982, Landstroem et al. 1993, Berglund et al. 1996), this article is supposed to supplement the overview with some contemporary publications. It also includes older publications which were not mentioned in other review articles or were not described there in detail. The presented review concentrates on the effects of low frequency noise up to 100 Hz on selected physiological parameters, subjective complaints and performance. The influence on the loudness judgement and the annoyance is not taken into account. Animal experiments do not receive attention, too. Some graphics ease the interpretation of the scientific results.

Sensation of Low Frequency Noise (LFN) - the thresholds of hearing, vibrotactile perception and aural pain

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The knowledge of the hearing threshold is essential for the analysis of effects of LFN. [Figure - 1] shows the thresholds up to 250 Hz measured by different authors (Robinson et al. 1956, Corso 1958, Yeowart et al. 1967 and 1974, Whittle et al. 1972, Landstroem et al. 1983, Verzini et al. 1999). The inclusion of further data would probably not change the trend obvious from [Figure - 1]. There is only little data with a fairly variable range based on studies of about 260 persons aged between 16 years (Robinson et al. 1956) and 70 years (Whittle et al. 1972). All published results were given as mean values and standard deviations. No but one article presented the median values and/or percentiles and/or extreme values. Robinson et al. (1956) supplied the median values, which were strongly related to the mean values, perhaps because of the large study group of 120 subjects. In order to generate a range of representative thresholds in [Figure - 1], standard deviations reported were added to the highest mean value and subtracted from the lowest mean value. Perhaps, the thresholds varied because of the used measuring method and the between- and within-subject differences. The maximum ranges given in [Figure - 1] varied between 20.1 dB and 29 dB at 4, 5, 25, 32, 40, 50, 75 and 100 Hz. The variability of the individual thresholds of the study participants was probably larger, but, as mentioned above, the authors did not report on the extreme values. Landstroem et al. (1983) investigated the threshold of "vibrotactile" perception. The results suggest no differences between deaf and hearing subjects. Therefore, the mean values of both groups were presented in [Figure - 1]. The subjects described a frequency-dependent sensation of vibration of different parts of the body (lumbar, buttock, thigh, calf).

Only one paper was found with information about the threshold of aural pain (von Gierke et al. 1976, see [Figure - 1]).

Aural effects of low frequency noise 

Although there are different opinions concerning the role of the temporary threshold shift (TTS) as a predictor of the permanent threshold shift (PTS), it is assumed that a better method does not exist at present. The TTS is not appropriate for calculating the individual noise induced hearing loss, but it is useful for predicting the PTS of groups of persons exposed to noise of certain levels and types (Sataloff et al. 1993). [Figure - 2] summarises the scientific results regarding the aural effects like TTS, PTS and a sensation of pressure in the ear in relation to the hearing threshold and the threshold of aural pain.

A number of authors obtained *temporary threshold shifts* in laboratory experiments or field studies. Alford et al. (1966) and Jerger et al. (1966) found TTS (10 dB - 22 dB) in 11 of 19 subjects after 3 minutes repeated exposure to 119 dB - 144 dB / 2 Hz - 12 Hz. The TTS was observed in the hearing frequency range from 3 kHz to 8 kHz. Nixon (1973) reported on TTS (20 dB - 25 dB) in one of three participants caused by exposure to 135 dB / 18 Hz (6 times 5 minutes exposures) and 140 dB / 14 Hz (steady exposure, duration 5 min - 30 min). Johnson (1973, cited in Johnson 1982) recorded TTS (8 dB) in the hearing frequency range from 2 kHz to 6 kHz due to exposure to 140 dB / 4 Hz, 7 Hz, 12 Hz in one of eight subjects (duration 5 min). A prolonged exposure time (30 min) caused TTS from 14 dB to 17 dB (one exposed subject only).

Mills et al. (1983) obtained TTS of different degrees and depending on the frequency of the noise (octave band noise, centred at 63 Hz, 125 Hz or 250 Hz) in 52 subjects. A 24-hour exposure to 84 dB(A) led to TTS from 7 dB to 15 dB in the frequency range from 300 Hz to 500 Hz. An 8-hour exposure to 90 dB(A) caused TTS from 12 dB to 17 dB in the frequency range from 250 Hz to 700 Hz. Tonndorf (1950) reported on temporary hearing impairments determined by tuning-fork test in employees which worked in engine rooms of submarines (infrasound 10 Hz - 20 Hz), but no sound pressure level was given.

In contrast, *no TTS* was found by the following authors: Slarve et al. (1975) recorded no TTS in four subjects after exposure to pure tones for a period of 8 minutes. The frequencies ranged from 1 Hz to 30 Hz (125 dB - 144 dB). Johnson (1973 and 1980) found no TTS after various exposure conditions (126 dB - 171 dB / 0.6 Hz - 10 Hz / 1 min - 26 min / 1 - 16 subjects). Mohr et al. (1965) applied several different exposure conditions (see paragraph "subjective complaints"). The authors discovered no effects on the hearing threshold even due to the exposure to the highest levels (narrow band noise, overall sound pressure levels 149 dB - 154 dB / maxima at 2 Hz - 10 Hz for 2 minutes, tests 9, 10 and 11). However, it is difficult to interpret the results, because it is not clear, which subject wore ear protectors for which period of the exposure.

Several investigations revealed *subjective aural complaints*. Karpova et al. (1970) reported on pressure in the ear after exposure to industrial infrasound (5, 10 Hz / 100, 135 dB) for 15 minutes. Slarve et al. (1975) described similar effects. Subjects told painless pressure in the ear during 8 minute exposure to 144 dB / 1 Hz - 20 Hz. A "sensation reflecting pressure build-up in the middle ear" occurred in the tests number 9, 10 and 11 of Mohr's experiments (see above) during exposures without ear protection, whereas three of the five persons also described a "tympanic membran tickle sensation". Two of three subjects experienced middle ear pain during "brief" periods without ear protection exposed to narrow band noise, overall sound pressure levels 143 dB - 145 dB / maxima at 25 Hz - 40 Hz (tests 12, 13, 14).

Only one epidemiological study of *permanent hearing impairments* could be found. Doroshenko et al. (1983) investigated 216 compressor operators exposed to infrasound (91 dB - 119 dB) and combined steady noise within the hearing frequency range (84 dB(A) - 97 dB(A)) for a daily period of 6.5 hours in a cross sectional study. The control group consisted of 220 workers exposed to industrial noise (93 dB(A) - 106 dB(A)) without any infrasound. The duration of exposure lasted from 1 year to 20 years. The mean age ranged from 20 to 50 years. Combined low frequency and steady noise exposure caused significantly increased hearing thresholds verified by

tonal audiometry as well as deteriorated intelligibility of whispered speech in comparison with the isolated industrial noise exposure. The differences enlarged with the length of exposure.

#### Non-aural effects of low frequency noise



LFN can cause a lot of non-specific physiological reactions, subjective complaints and an impairment of the performance. The [\[Figure - 3\]](#)[\[Figure - 4\]](#) show the results of numerous studies in relation to the hearing threshold and to the threshold of aural pain.

#### *Vascular, respiratory and endocrine effects, balance and visual disturbance*

Danielsson et al. (1985) investigated the effect of LFN on blood pressure, heart frequency and serum cortisol. 20 male study participants were exposed to pure tones at different levels (95 dB, 110 dB and 125 dB) and frequencies (6 Hz, 12 Hz and 16 Hz) for 20 minutes in the first series of experiments. In the second set of experiments, a one-hour exposure (125 dB, 16 Hz) was followed by a silent control period. On alternate days, the same subjects were exposed to either infrasound (125 dB / 16 Hz) or a so called control exposure (50 dB / 50 Hz, just 5 dB above the mean hearing level). The one-hour exposure to LFN led to a significantly increased diastolic blood pressure and a significantly decreased systolic blood pressure in comparison with the control exposure. No significant changes of the heart rate and serum cortisol were obtained. Landstroem et al. (1983) exposed 10 normal hearing and 10 deaf subjects to 115 dB / 6 Hz for 20 minutes. In normal hearing volunteers changes of EEG patterns - interpreted as diminished wakefulness -, alterations of systolic and diastolic blood pressure and of heart rate were observed. These effects were not found in deaf persons. No differences in vibrotactile sensation were detected between both groups. Therefore the authors attributed the observed physiological effects to cochlear stimulation. Karpova et al. (1970) obtained the following physiological reactions caused by 15 minutes exposure to 5 Hz and 10 Hz simulated industrial infrasound (100 dB and 135 dB): significantly decreased respiration rate, "depression of the encephalic haemodynamics", changes of EEG patterns, increased heart rate, reduced heart muscle contraction strength. Wysocki et al. (1980) reported on tendencies of decreased heart rate, diminished electrical conductance which may result from the peripheral vascular changes and reduced skin temperature. 40 subjects were exposed to a low frequency spectrum typical for vehicles (control group: 20 subjects, no exposure). Evans et al. (1972) recorded vertical nystagmus and described a subjectively reported "feeling of body sway" in 25 subjects exposed to pure tones (2 Hz - 10 Hz) above 130 dB. The effects were primarily pronounced at 7 Hz. The authors developed a threshold curve for vertical nystagmus induced by a 7 Hz binaural signal. No level of the infrasound (1 Hz - 20 Hz / 115 - 120 dB) caused any visual disturbance. Takigawa et al. (1988) examined the influence of infrasound (5 Hz and 16 Hz, 95 dB, 5 minutes) on the control of upright standing posture. The authors concluded that the excitability of the vestibulum seemed to be accelerated by LFN, whether or not the subjects perceived any sensations. Doroshenko et al. (1983, methods see above) reported on significantly abnormal findings regarding the vestibular functions in the exposed group (test of statokinetic function, calorific test, rotational test). Wayne et al. (2002) exposed 32 subjects to a low frequency noise and a reference noise with a flat frequency spectrum at the same A-weighted sound pressure level (40 dB (A)). For the LFN, sound pressure levels in the frequency region of 31.5 Hz to 125 Hz were added. Higher cortisol levels (six saliva samples during the two-hour exposure) were associated with high sensitivity to noise and being exposed to LFN (significant interaction). This association was not found for the reference noise.

#### *Subjective complaints*

Slarve et al. (1975) exposed 4 subjects to a low frequency spectrum which contained pure tones (1 Hz - 30 Hz, 125 dB - 144 dB) for 8 minutes. The study participants reported on voice modulation and body vibration (abdominal, chest). Harris et al. (1978) exposed 40 subjects to 7 Hz / 125 dB, 132 dB and 142 dB, partly combined with 110 dB low frequency background noise. The authors mentioned spontaneous complaints in six study participants following exposure to 7 Hz / 142 dB (vibrationsensation, pressure in the ear, inability to concentrate). Verzini et al. (1999) reported on a feeling of vibration, pressure and annoyance in the head, the ears and the nape during exposure to 10 Hz / 110 dB tones or to a similar LFspectrum. The results of Slarve et al. (1975), Harris et al. (1978) and Verzini et al. (1999) correspond with the findings of Landstroem et al. (1983) that the sensations of vibrations caused by airborne noise occur about 20 dB above the hearing threshold (see [\[Figure - 1\]](#)). The investigations of Ising et al. (1979 and 1980) were the only experimental ones which used prolonged exposures up to 8 hours for 10 days (3 Hz - 24 Hz / 110 dB). The subjects reported on a lack of concentration, annoyance, tiredness, tense, irritability and restlessness. Wayne et al. (2002, see above) did not find a significant difference between LFN and the reference noise for the mood dimensions or for the subjective symptoms rated by questionnaires. However, the anxiety of the subjects estimated with the Trait and State Spielberger's scales modulated the subjective judgements (semantic differential scales). For example, there was a strong relationship between the trait "anxiety" and the acceptability to the tone exposure. Landstroem et al. (1988) studied the effects of different levels of LFN in two types of lorries in a field investigation with 13 lorry drivers. Subjectively rated increased fatigue was more pronounced when driving the lorry with higher LFN level. The results were supported by the objective EEG and ECG recordings. Tesarz et al. (1997)

investigated 439 persons working in offices, laboratories and industries. The dominance of LFN at the workplace was determined by the difference between C- and A- weighted levels. No person was exposed to noise with C-A differences greater than 20 dB. Fatigue and tiredness after work increased with increasing dominance of LFN. Karpova et al. (1970, see above) described complaints following exposure to LFN: fatigue, feeling of apathy, loss of concentration, somnolence and depression. Doroshenko (1983, see above) analysed the anamnestic data and

found that the compressor workers complained about increased irritability, headaches, periodic vertigo attacks, increased sweating and tiredness, sleep disturbances, pains in the region of the heart and difficulty in breathing.

Mohr et al. (1965) carried out systematic investigations with different types of LFN exposures of very high level. The following subjective sensations were described:

- (1) minor chest wall and body hair vibration due to
  - a) 124 dB / 10 Hz - 400 Hz broad band noise for 2 minutes (test 1), one of five persons without ear protection
  - b) 114 dB - 133 dB / 35 Hz - 140 Hz octave band noise for 2 minutes (test 2), one of five persons without ear protection
  - c) 144 dB / 4 Hz - 4 kHz broadband noise for 1 minute (test 3), no information about wearing of ear protection
- (2) "awareness of respiratory action" during test 3
- (3) sensation of moderate chest wall vibration, hypopharyngeal fullness (gagging), perceptible visual field vibration, prolonged post-exposure fatigue caused by 143 dB - 145 dB / 10 Hz - 60 Hz narrow band noise (tests 12, 13, 14), no information about wearing of ear protection
- (4) abdominal wall vibration due to 150 dB - 154 dB / 10 Hz - 20 Hz narrow band noise for 2 minutes (tests 9, 10 and 11) and nostril vibration during test 10 (5 Hz - 10 Hz), no information about wearing of ear protection

The highest pure tone exposures produced with the help of a siren were used to check the voluntaries tolerance threshold (140 dB - 154 dB / 40 Hz - 100 Hz, 3 subjects, test 16). All three subjects wore ear protection. It was decided to stop the exposure, because the following alarming responses occurred: (1) transient headache (one subject only) at 50 Hz / 153 dB, (2) coughing, substernal pressure, choking respiration, salivation, pain on swallowing, hypopharyngeal discomfort, giddiness, testicular aching (one person only) at 153 dB / 60 Hz and 150 dB / 73 Hz, (3) mild nausea, giddiness, subcostal discomfort, cutaneous flushing, tingling at 153 dB / 100 Hz. All study participants suffered from evident post-exposure fatigue.

### ***Performance***

Evans et al. (1972, see above) presented a random sequence of illuminated shapes which had to be recognised by the subjects. Relatively low levels (115 dB) caused a 30% - 40% increase of the choice reaction time. Harris et al. (1978, see above) revealed no significant effects on a serial search task and a complex counting task for the infrasound exposure in comparison with the 110 dB background noise. Wysocki et al. (1980, see above) also used a serial search task and analysed the threshold of speed for the stimuli presentation. A significantly increased threshold was found in the exposed group. Waye et al. (2002, see above) obtained a significantly decreased subjectively judged working capacity due to LFN compared with the reference noise. Additionally, LFN caused a more pronounced deterioration of highly demanding task performance (proof-reading task and verbal grammatical reasoning task). For both tasks, subjects highly sensitive to noise showed a poorer task performance. This effect could not be found for routine-type tasks (see also Bengtsson et al. 2000 and Waye et al. 2000). Karpova et al. (1970, see above) mentioned lengthened visual motor responses to stimuli. Benignus et al. (1975) exposed 27 subjects to broadband noise (11.5 Hz - 44 Hz and 91 Hz - 350 Hz, both 80 dB, control condition: no exposure). The rate of misses in a vigilance task increased significantly during both noise conditions. Schust et al. (2002) exposed 12 subjects to a LFN spectrum recorded on the bridge of a ferry boat (main energy in the range of 10 Hz - 100 Hz, 81 dB - 99 dB) and a reference noise with a flat spectrum (55 dB - 65 dB for all 1/3 octaves up to 20 kHz) recorded in the machine room. Both noise conditions had the same A-weighted level of 70 dB(A) for 48 minutes. A barely significant difference was found for the sum score of "concentration" and "alertness" rated by questionnaire. A greater impact of LFN was obvious. Moreover, the detection time (signal detection test) shortened during the reference noise exposure, whereas it remained constant during the LFN period. This difference approached significance.

A number of publications deal with the so called Vibroacoustic Disease (VAD - see Aviation, Space, and Environmental Medicine 70 (1999) 3, section II, Supplement). In view of this issue, Gomes et al. (1999) examined 40 workers who have been employed as aircraft technicians for 22 years in average and 30 educationally and age-matched controls. The exposure was assumed to be more than 90 dB in the range below 500 Hz. Significant differences occurred only in one sub-scale of the two applied performance tests, where the controls had better results. However, the P300 event-related brain potential showed significantly prolonged latencies and significantly smaller amplitudes in the occupationally exposed group.

### **Discussion**



Hypothetically, effects of LFN may be mediated through different ways: (1) vibration of the eardrum, leading to a hearing sensation through pressure changes in the cochlear endolymph, activation of the hair cells and the acoustic nerve, (2) direct energetic transmission of the airborne acoustical sound waves into the cochlear endolymph or into the acoustic nerve, that means pressure changes in the cochlear endolymph without involvement of the eardrum or excitation of the acoustic nerve without involvement of the eardrum and the

endolymph, but both leading to a hearing sensation (a rather unlikely hypothesis as long as the middle ear is intact because of the higher impedance of this way in comparison with (1); more probable, (2) might act additionally to (1)), (3) excitation of the vestibular system, (4) excitation of receptors and/or nerve fibres in the skin or in any other kind of tissue or blood vessels within the organism - e.g. the optic nerve, mechanoreceptors and baroreceptors responsible for the control of the blood pressure - by direct energetic transmission of the airborne acoustical sound waves. Following these hypotheses, on one side, a determination of the thresholds of hearing, of vibrotactile perception and of aural pain [Figure - 1] requires a conscious sensation of the stimulus. On the other hand, other biological reactions could arise even below the perception thresholds. Particularly, the pathways (3) and (4) do not presuppose conscious sensations. Bearing these pathways in mind, the scientific results shall be discussed now.

### *Aural effects*

The function of the hearing organ was checked with the tone audiometry in the presented studies. This method is a subjective one. It requires an active involvement of the study participant and a conscious hearing of LFN. Acoustic stimuli affecting the hearing organ are supposed to activate the ways (1) or (2) mentioned above. That means, they accordingly cause a hearing sensation. The methods for the estimation of the resting hearing threshold and for the measurement of temporary or permanent shifts of the hearing threshold (TTS or PTS) activate the same sensory pathways. Consequently, it may be assumed that the TTS or PTS estimated by audiometry appear due to acoustic stimuli above the individual hearing threshold. The results unquestionably confirm this assumption. In [Figure - 2], the only exposure condition below the hearing threshold which was associated with a threshold shift was part of a LFN spectrum (Doroshenko et al. 1983). Perhaps, the acoustic energy above the hearing threshold was responsible for the effect. The combined steady noise within the hearing frequency range could also explain the obtained threshold shift.

Apart from that, there is a need for further scientific research. No publication described LFN-induced threshold shifts in the relevant low frequency hearing range. The measured audiometry frequencies were not reported in most of the papers. The resting hearing thresholds of the subjects were not given for the low frequencies. It can be assumed, therefore, that only the conventional audiometry range from about 500 Hz to 6 kHz was checked.

Additionally, the use of objective methods like the recording of brainstem potentials or otoacoustic emissions could lead to different results concerning the hearing threshold or the impairment of hearing due to LFN exposure.

A sensation of "pressure in the ear" might be caused by baroreceptors located in the tissue of the ear channel or in the adjacent tissue around the cortical organ (pathway (4)). From this point of view, the sensation could occur below the hearing threshold. On the other hand, as mentioned above, this pathway is quite implausible as long as the middle ear works properly. The results support these doubts. Only Mohr et al. (1965) noticed a sensation of pressure in the ear due to 129 dB / 1 Hz as a part of a LFN spectrum (see [Figure - 2]). Perhaps, the acoustic energy of the sound above the hearing threshold caused this perception. These results correspond with the findings of Landstroem et al. (1983). Two of the 10 deaf subjects could "feel the sound through their ears", based on a sensation of vibrations and pressure changes in the ear ("pseudoauditory air conduction"), but only when the levels exceeded 120 dB (4 Hz - 25 Hz). These sound pressure levels lie above the hearing threshold.

The studies of Johnson (1973, cited in Johnson 1982) with very high sound levels remain to be discussed. There were two subjects exposed above the threshold of aural pain without reporting on TTS or pain. But the original paper did not talk about these experiments, so that the results cannot be judged. Maybe, the subjects wore ear protection. Johnson (1982) described an experiment he experienced himself. He listened to 172 dB / 4 Hz for less than 30 seconds by using an earcup. He felt no pain but a "massaging" of the tympanic membrane. He concluded, that damage could occur to the middle ear without previous pain. Summarising the present knowledge, this conclusion could be supported.

### *Non-aural effects*

#### *Subjective complaints*

A conscious perception is to be presupposed for the sensation of vibration of different parts of the body. Therefore, such effects should arise around or above the threshold of vibrotactile perception [Figure - 1]. The present results confirm this assumption (see [Figure - 3],[Figure - 4]). However, sensations concerning the vestibular system (pathway (3)) or other sensors including vibration sensors (pathway (4)) might appear below the hearing threshold. Actually, some investigations revealed complaints like somnolence, irritability, tiredness, tense and restlessness, below or at least near the hearing threshold (Ising et al. 1979 and 1980, Karpova et al. 1970, see [Figure - 3],[Figure - 4]). The other sound levels, which were associated with subjective complaints and ranged below the hearing threshold in [Figure - 3],[Figure - 4] (Doroshenko et al. 1983, Landstroem et al. 1988), were part of a broader LFN-spectrum. Nevertheless, the revealed complaints - like increased fatigue, irritability, headaches, periodic vertigo attacks, increased sweating and tiredness, sleep disturbances, pains in the region of the heart and difficulty in breathing - might be caused by the lower frequency parts of the spectrum, too.

#### *Vascular, respiratory and endocrine effects, balance and visual disturbance*

As already argued above, these effects might emerge due to exposure below the hearing threshold, because the

pathways (3) and (4) perhaps do not presuppose a conscious perception of the LFN by the cortical organ. The findings seem to support this deduction. Danielson et al. (1985) and Karpova et al. (1970) reported on changes in blood pressure, respiration rate, EEG patterns and heart rate caused by exposure below or near the hearing threshold (see [Figure - 3](#)). The low level exposures used by Wysocki et al. (1980), Waye et al. (2002) and Doroshenko et al. (1983) also comprised acoustic energy above the hearing threshold. Nevertheless, the reported effects - like changes in heart rate, peripheral vascular blood flow, skin temperature, cortisol levels and vestibular functions - could have been triggered by the lower parts of the frequency spectrum.

### **Performance**

The same arguments as mentioned above are assumed to be valid for the influence of LFN on the performance. Evans et al. (1972) and Karpova et al. (1970) found lengthened visual motor responses caused by LFN exposures below or near the hearing threshold. The impairment of performance obtained by Wysocki et al. (1980), Waye et al. (2002) and Benignus et al. (1975) could be generated by the lower frequency parts of the spectrum below the hearing threshold, too (see [Figure - 3](#)).

### **Conclusions**



There is a clear frequency dependence of the hearing threshold in the low frequency range with a steep slope compared with the middle frequency range. On the other hand, the threshold of aural pain is less dependent on the frequency. It varies from 130 dB at middle frequencies around 1 kHz to 160 dB at very low frequencies. Consequently, the dynamic range between the thresholds of hearing and of sensation of pain diminishes with decreasing frequency ([Figure - 1](#)). Moreover, the equal loudness contours narrow with diminishing frequency (Robinson et al. 1956). Because of the reduced dynamic range, small changes of the LFN stimulus can cause great differences of the response effects. Therefore, different individual effects may be expected even under similar exposure conditions. This should be taken into account by the setting of limits concerning the health risks. Sufficient safety margins are recommended. The use of a frequency weighting with an attenuation of the low frequencies (e.g. G-weighting) does not seem to be appropriate for the evaluation of the health risks caused by LFN up to 100 Hz. There is no scientific evidence for an association between a frequency-weighted sound pressure level and the biological effect. It may be proposed to measure third octave band spectra or narrow band spectra. A comparison with the known human responses caused by the measured levels and frequencies could help to evaluate the health risks.

The knowledge reviewed in this paper is mainly based on laboratory studies. Only a few field studies were found. A comprehensively critical view of methodological issues concerning these types of investigations was given by Berglund et al. (1996). Moreover, the authors provided recommendations for further studies. The proposals are still up to date. They shall to be only shortly noticed here:

- (1) investigation of effects of different frequency spectra
- (2) prolonged exposures in laboratory studies
- (3) realisation of longitudinal epidemiological studies
- (4) use of the rare occasions of noise source changes for epidemiological studies (e.g. opening of new freeways or airports)
- (5) measurement and statistical control of confounding factors
- (6) consideration of individual differences (7) taking into account various risk groups
- (8) development of standardised techniques to measure LFN
- (9) realisation of laboratory studies of various features of noise signals
- (10) investigation of the relative contributions of LFN, impulsiveness and tonality to the human response
- (11) study of the relative importance of vibration and rattle versus LFN
- (12) development of methods for LFN attenuation and control measurement technology

Additionally, some more proposals could be made as a result of this review:

- (1) The measurement of the individual hearing threshold and the vibrotactile threshold for airborne LFN in the exposed frequency range could be helpful for the judgement of the obtained effects. The objective methods like the recording of brainstem potentials or otoacoustic emissions should be considered, too.
- (2) In laboratory experiments, an exposure via loudspeakers (whole body exposure) probably better reflects the practically environmental conditions than the use of headphones alone. On the other hand, headphones can be employed to distinguish the ways of sensation of LFN. The exposure to LFN near or above the vibrotactile

threshold via loudspeaker could lead to different effects compared with pure headphone exposure.

(3) Experiments with hearing versus deaf persons or with/without ear protection ought to be carried out to clarify the pathways of LFN sensation.

(4) The hearing threshold shifts in the frequency range of the exposure should be determined (see discussion of aural effects).

(5) The level of the airborne noise and the body vibration caused by this airborne noise or by other sources ought to be measured simultaneously. Appropriate methods for laboratory and field studies were described by Takahshi et al. (1999 and 2001) and Smith (2002).

(6) Combined effects of LFN and body vibration should be taken into account. There is some evidence of mutual effects of both factors at least concerning the thresholds of hearing and vibrotactile sensation (Sueki et al. 1998) and the influence of vibration on the equal loudness level contours (Bellmann et al. 1999).

(7) A cause-effect modelling ought to be tried to analyse the transmission of the acoustic energy from the input into the body to the structures containing sensors, like the Membrana basilaris, the adjacent tissue around the Nervus cochlearis, the vestibular system, the skin layers, the inner organs, muscles etc. Bearing this in mind, individual features could be of interest, e.g. anthropometric characteristics like height, subcutaneous fat layer, muscularity etc.. For example, Takahshi et al. (1999) found a negative correlation between the measured noise-induced vibration and the subject's body mass index.

(8) Different risk groups like children or pregnant women should be considered (for arguments see point 7)[\[47\]](#).

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Figures

[\[Figure - 1\]](#), [\[Figure - 2\]](#), [\[Figure - 3\]](#), [\[Figure - 4\]](#)

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