Acoustics'08
Paris
June 29-July 4, 2008
www.acoustics08-paris.org

Effective protection of the sense of hearing is prevented by ISO1999 noise standard

Gerald Fleischer

Liebig University School of Medicine, Aulweg 123, 35392 Giessen, Germany
gerald.fleischer@gmx.net

To determine auditory performance in a simple way, pure-tone audiometry is being used. While health-related diagnostics is generally becoming more and more refined, ISO1999 is demanding rather rudimentary procedures. Both, frequency range and number of test frequencies are reduced, making it impossible to use modern and effective analytical tools such as pattern recognition. There is a clear relation between pressure-time-history of impulses and the details of the resulting auditory damage. But this relation can only be recognized if the restrictions of this standard are being ignored. Typical examples of audiograms from a large data base will be presented, showing simultaneously the data according to ISO1999 and in more modern ways. It will also be demonstrated how useful the tool of pattern recognition can be, for analysis of damages as well as for preventive measures.

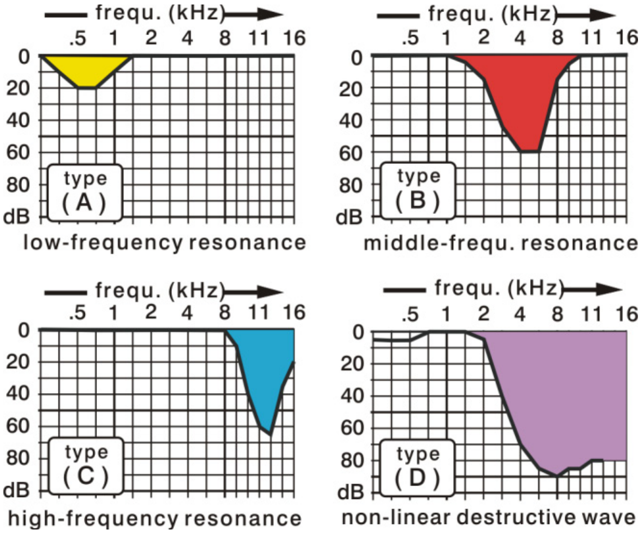
1 Introduction

For two decades Auditory Research is working on the relation between the acoustic environment and auditory performance. Hearing capability is determined by thorough pure-tone audiometry from 125 Hz up to 16 kHz, that includes control procedures within every audiometry session to increase reliability. Two different approaches as to the persons examined are applied. One is called the archive of auditory impulses. We are collecting data on persons that have been exposed to acoustic events that caused auditory damage. Everything about ear and hearing of these individuals is recorded, including the audiogram. If it is possible at all, the damaging event is being re-enacted as accurate as possible, in order to make acoustic measurements. For this purpose a dummy is being used that is especially designed for powerful impulses, with peaks up to 188 dB. Measurements are simultaneously taken with the dummy and with a free-field microphone on top of the dummy. In both cases the pressure-time-history is being recorded, with a sampling rate of 100 kHz. Such accidents and mishaps do not only occur at the workplace, but are also produced by toys and tools during many other activities. Hence, the age of such persons ranges from about 6 years to 70 years.

The other approach is the examination of entire groups, as completely as possible. One big advantage is that we can learn about hearing in groups that do not – or nearly not – show up in the medical service. Groups examined are office personnel, orchestra musicians, construction workers, fire fighters, airline pilots, friends of discotheques, congenitally blind persons, Tibetan monks, and many more. These voluntarily cooperating persons get a medical checkup of the ear, to make sure that ear is healthy. If they have no prior audiometric experience they get a training session before the audiogram is being taken. Everyone gets an interview as to his or her previous acoustic environment and ear-related activities, and the result is documented. – All together we now have data on roughly 11 thousand persons in our data base.

2 Effects of impulses

Looking through our data on impulses it is apparent that the distance between the impulse and the ear is of utmost importance. Quite often damaging impulses are not particularly loud, but they occured unusually close to the victims. It is important to emphasize that such harmful impulses can damage the ear in a really quiet environment. This demonstrates that impulses are an independent type of damage, and not a special effect of continuous noise. Ears affected by powerful impulses show four basic types of damage, Fig. 1.



low-frequency resonance
middle-frequ. resonance
high-frequency resonance
non-linear destructive wave

Fig.1 The footprints of powerful impulses. These major types of damages can be caused by a single impulse.

Type A is caused by powerful low-frequency impulses, such as older driver- or passenger airbags, or heavy machinery that is hitting another big peace of equipment. In the vicinity of heavy weapons there are also such types of damage, although in those cases they are usually combined with damage of type D. Type B is the familiar c5-notch and it is typical that they are caused by bursts of loud signals. Type C is the damage resulting from exposure to very high frequencies, with a small distance to the ear, practically always less than one meter. The duration of the impulses is very short, less than 1 ms. Toy pistols cause such damage, or traditional Chinese fire-crackers, or the signals of lithotripsy at the duct of the parotid gland. It may be argued that these high frequencies are not that relevant for hearing. However, such injury can cause tinnitus, in some cases for life, and so it should certainly be included into protective strategies. From our own experience we know that many children suffer enormously from tinnitus.

Finally there is type D where the entire high-frequency range of the cochlea has been ruined. Such damage is always the result of a very powerful impulse, like the shot of a modern weapon nearby, or even of a blank pistol at close range. One single impulse, lasting about 1 ms, can cause this massive damage. It can be assumed that a non-linear destructive wave inside the cochlea is doing this damage at the high-frequency end. Of course, there is some variation to these four typical patterns, as to the severity and the shape of the damage.

At this point it is important to notice that such damages are not caused by long-term exposure. Instead, such patterns in the audiogram clearly indicate that the damage was caused by one or a few impulses. According to ISO1999 [1] the usually applied six frequencies – from 0.5 to 6 kHz – do not permit to detect and analyse such patterns. Hence, it is necessary to use a thorough audiometry at many frequencies for pattern recognition.

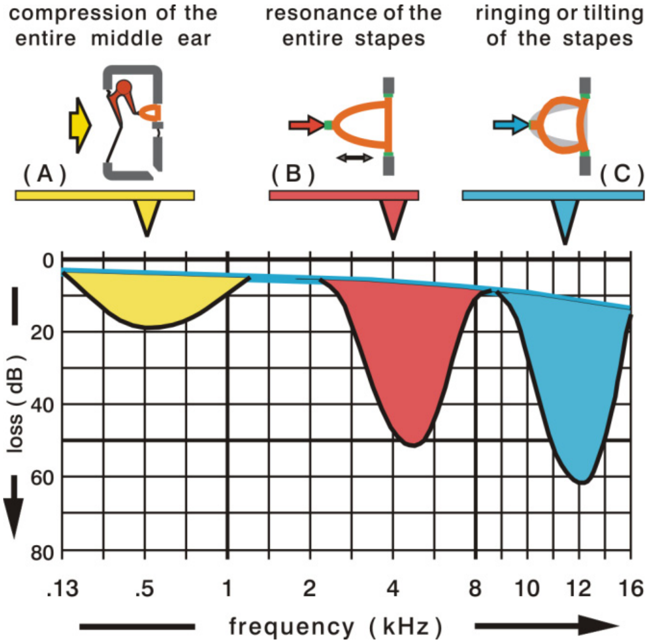


Fig. 2 Three types of resonances within the middle ear and their effect on noise-induced damages.

Combining our knowledge of the ear, with our data on effects of impulses, and with discussions in the literature, it can be concluded that there are three resonances in the middle ear, Fig. 2. The curved blue line in this illustration is an age-line that will be discussed next. As indicated earlier, type D (Fig. 1) is very likely caused by non-linear destructive events at the base of the cochlea..

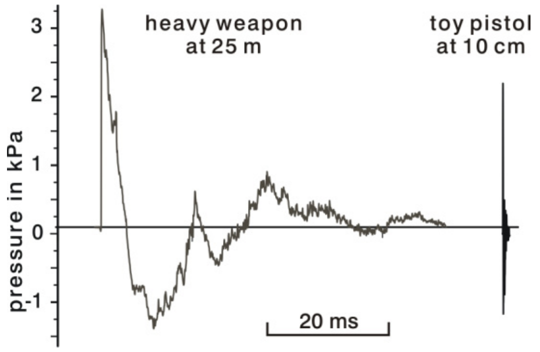


Fig. 3 Two acoustic impulses of very different effect on the ear (free-field microphones).

Pressure-time-history of impulses varies to a great extent, Fig. 3. The heavy weapon typically causes damage of type A and D combined, while the brief signal of the toy pistol results in damage of type C. Reason for this is the different stimulation of the complex vibrating system of our ear.

3 Aging of the sense of hearing

Studying individuals of various age showed the need to get a hold on normal aging. During the years 1995 to 1998 data on pure-tone audiometry were collected, here in central Europe, on men and boys, ranging in age from 6 to 70 years. All together data on a total of 4 400 persons were collected and could be analysed. Persons with diseases of the ear, with sudden hearing loss, and with strong auditory damage were not included. Everyone unfamiliar with audiometry got a training session before the real audiometry was performed. The data were combined in groups of age covering a decade, and the results smoothed somewhat, Fig. 4. These lines – so-called age-lines – were created on a yearly basis by means of interpolation.

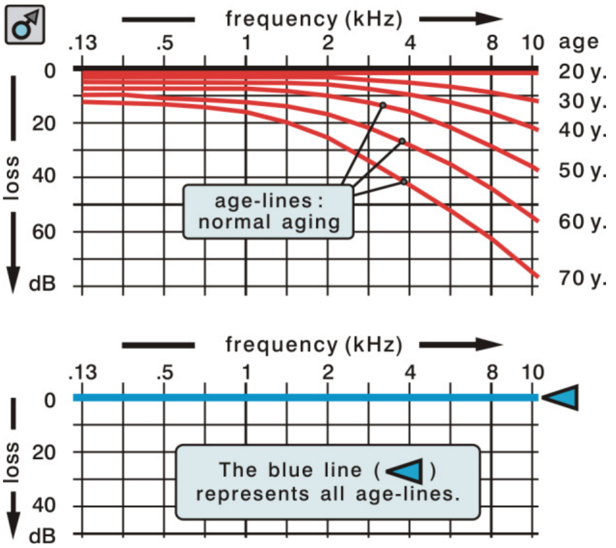


Fig. 4 Age-lines represent normal aging of the ear

The age-lines represent normal hearing for a certain age, and with this tool it is possible to compare the individual audiogram not with the threshold of young adults, as usual, but with normal hearing at the age of the individual. In this way it is possible to study the auditory performance of entire groups, independent from the age of the individuals. It can be achieved by straightening the age-line into a straight line, independent from the age of the individuals, as in the lower part of Fig. 4. This blue horizontal line represents normal aging. Hence, not only individuals, but entire groups of persons can be presented in one diagram. Such a technique makes it possible to clearly define auditory damage, because it is restricted to the area below the age-line. In Fig. 2 there is an age-line, demonstrating this principle.

There is no generally accepted definition about auditory damage, but it is customary to accept a scattering of 20 dB. So it was defined to declare an ear as damaged if one – or several – audiometric points are more than 20 dB below the age-line of the individual. To achieve this analysis a computer program was developed, Fig. 5. It automatically separates every group examined in two sub-groups. One is comprised of ears who are said to hear normal, because no audiometric value is more than 20 dB below the corresponding age-line. The other sub-group are ears that are categorized as damaged, because one or several audiometric points are more than 20 dB below the age-line.

As a result Auditory Group Curves are created, giving detailed information about the hearing capability of the group examined [2].

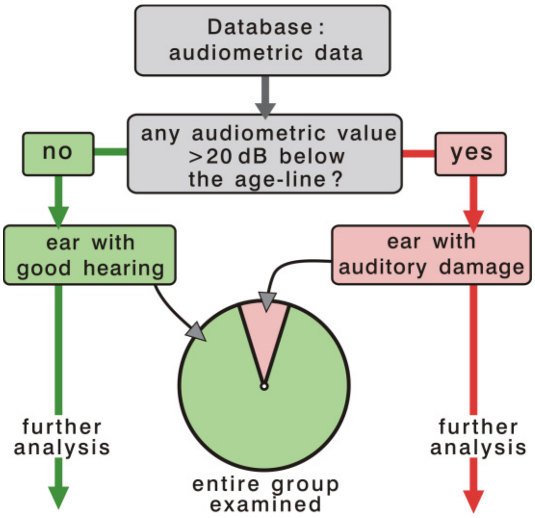


Fig. 5 Program for separating good-hearing ears from those with auditory damage

4 Long-term high noise levels

Persons exposed to high levels of more or less continuous noise for a very long time show other forms of damage in the audiogram, Fig. 6. Only the area under the age-line (here shown as curved blue line) is considered as damage. Such injury, caused by about two decades of very loud noise, is an irregular degeneration across the hearing range, without the pattern that is characteristic for powerful impulses. It is clearly shown by the two industry workers. The computer technician the spent lots of money and time to modify his car so that it is filled with a powerful audio system, and the special power-supply that is essential for such a "boom car". He too has auditory damage that does not present the typical pattern for impulses. – All audiograms presented in this article show permanent threshold shift (PTS).

Such data show that continuous noise is injuring the ear in another way as impulses. Even long-lasting continuous noise does not create the same pattern as impulses. Of course, persons working under loud occupational noise can have forms of damage that are characteristic of impulses. This is because they have been exposed to strong impulses. Someone working under low noise-levels can still show damage pattern for impulses, Fig. 1. Currently it is customary to deny that such a damage can occur at the workplace, because of the low level of continuous noise, but this is wrong.

According to our experience it can be estimated that about 75% of noise-induced auditory damage at the workplace in central Europe is caused by rarely occurring strong impulses close to the ear. In studies about permanent damage in children, caused by toy pistols, or by damages caused by new-year-celebrations there is no long-term continuous noise involved [3,4]. The same holds true for studies in remote parts of China, in areas with practically no technical noise, where damages by massive impulses during the celebration of festivities are widespread [5].

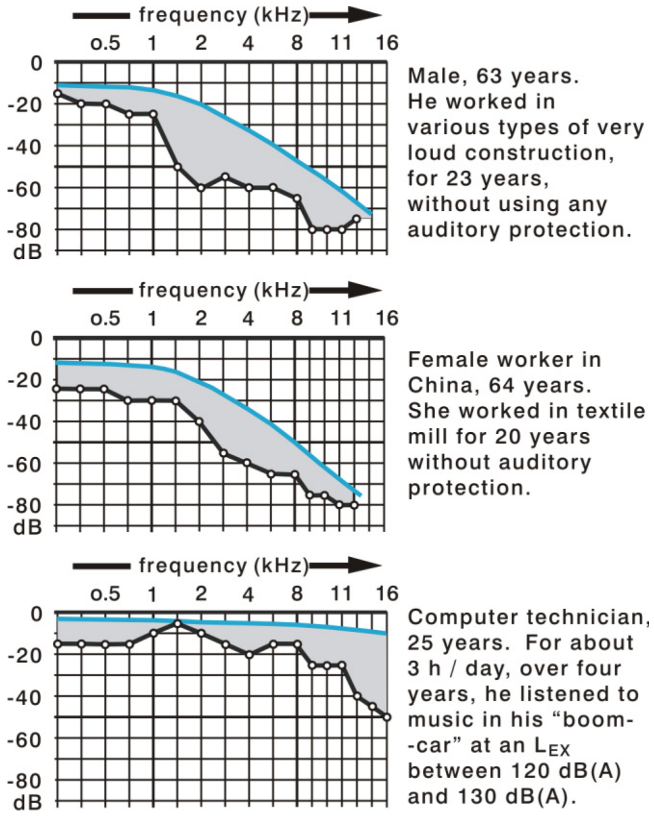


Fig. 6 Loud continuous noise for years and decades

To get a hold on the effect of the long-term sound level at the work place, a high-ranking research unit in the US collected individual data on exposure (L_{EX}) at the workplace, as well as the audiograms of the same persons. Analysing these valuable data with the group curve technique (Fig. 4, 5) results for the 139 men are shown in Fig. 7. 74 men were exposed to an L_{EX} ranging from 80 to 90 dB(A), and 39% of them showed auditory damage. The remaining 65 persons were working at an L_{EX} between 91 and 98 dB(A), and 34% of them showed damage. With the auditory group technique the severity of damage can be determined [2]. This is being done by averaging the individual loss across the frequencies examined for all persons with damage, and the result is shown on the right side of Fig. 7.

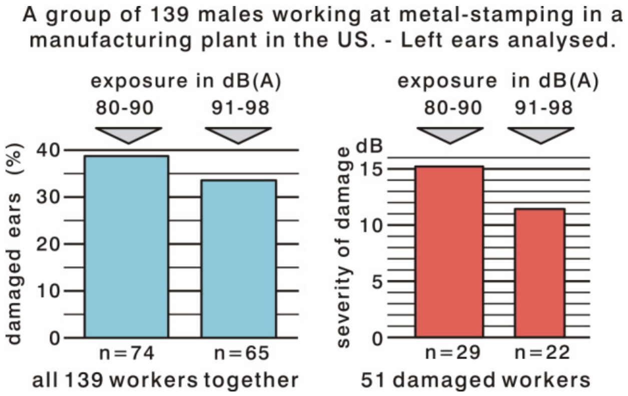


Fig. 7 Relation between long-term exposure at the workplace (L_{EX}) and auditory damage in a US plant. Data collected in 2005. Severity of damage = average loss relative to the age-line of every individual with damage.

From the 51 cases of damage 29 were working in the less loud range of L_{EX}, and – as a group – they showed an average loss of roughly 15 dB. The remaining 22 workers with damage were exposed to a higher noise-level, and their average loss relative to the age-line is roughly 12 dB. In other words, these data do not support the concept that the L_{EX} at the work place is the decisive factor for auditory damage. Data for the other ear of the same group of persons are similar, but for both ears, the differences between persons from low-noise areas, compared to those from high-noise areas are not statistically significant. But, looking at the audiograms, patterns related to powerful impulses are widespread. It can be summarized that data from this group of persons does not support the energy concept that is the basis for ISO1999. – A study of the literature on auditory performance of orchestra musicians [6] revealed that there is no apparent relation between the sound level and hearing threshold.

How can this be explained ? According to our experience most damages occur because, by unhappy circumstances, the ear was close to a powerful impulse. This is relevant at most workplaces, as well as during hobbies and play. Acute acoustic trauma, with exposure time in ms, is very widespread, and causes most of noise-induced damage. However, if a workplace is excessively loud it will certainly lead to chronic degeneration of hearing, as shown in Fig. 6. While measuring the L_{EX} for a workplace, such seldom occuring impulses are not measured, and even if someone stumbles across one it is discarded as atypical. Since noise-induced injury persists, the effects of rare events are important, and they accumulate. A powerful impulse close to the ear is of utmost importance, even it occurs only once a month, or once a year, or even once in a lifetime. And it cannot automatically be assumed that auditory damage in workers at loud workplaces is caused by the workplace, if the audiogram shows a pattern that points to an impulse. – There are two independent damaging mechanisms : powerful impulses and long-lasting high sound level. There is a relationship between the L_{EX} and chronic degeneration of hearing, but the more important strong impulses are practically ignored by ISO1999. Regulations for work places in the EU [7] include limits for peaks of impulses, but the practical details are nebulous. The EU regulation for the safety of toys [8] implicitly permits acoustic conditions by toys that are illegal at workplaces.

5 Training-effects

Studying the auditory threshold in various groups of persons reveals effects of positive training. In other words, entire groups of persons are hearing better than others [2]. Most orchestra musicians are hearing better than normal, and their ears are aging less than in the general population. Sound designers are hearing marvellously well, but sound technicians are characterized by damages due to excessive noise. The best performance showed the small group of organ tuners who tune old church organs, a job that creates an L_{EX} of about 90 dB(A), or somewhat higher. Congenitally blind persons really hear exceptionally well, and they depend on this capability for their own safety. And the same reason may be the cause for the excellent hearing of professional fire fighters who are often working in an unknown environment under bad visual conditions. Such trainings-effects can also be determined with the tool of auditory group technique. Analysis of such data clearly shows that the L_{EX} at the workplace – or the environment – is not the relevant factor. Instead, it can be seen that persons who depend on good auditory performance, and who are motivated to keep it this way, are hearing particularly well. The common saying “practice makes perfect”, apparently also applies to the sense of hearing.

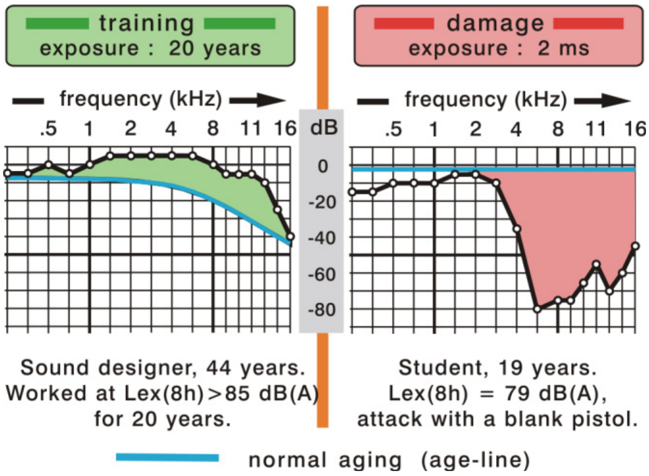


Fig. 8 Training versus damage: audiograms of two individuals

In Fig. 8 effects of positive training is contrasted with the damage caused by a single powerful impulse. Simple acoustic energy has no relation to the measured thresholds of hearing. However, an evaluation system for the effects of acoustic environment on hearing should be able to differentiate between these two conditions. Trainings-effects in experimental animals, on the cellular levels, have also been found [9].

6 Discussion

Analysing data from the archive of acoustic impulses clearly shows four major patterns of damages (Fig. 1), and, furthermore, damages due to impulses are much more widespread than damage due to long-term continuous noise. Pattern recognition requires reliable audiometric measurements at much more frequencies than those declared important in ISO1999. In other words, audiometry has to improve drastically so that automatic pattern recognition can be applied. The AHAAH-procedure (Auditory Hazard Assessment Algorithm for the Human)[10] does not show results related to patterns, since it is derived from a theoretical model based on the cat ear. Human damage patterns are important, because they are the result of real working conditions, and their appearance indicates that one or several strong impulses are responsible. Hence, long-term L_{EX} is not relevant in such cases. Therefore, a low L_{EX} at a particular workplace does not prove at all that such impulse-related damage can not have occurred. A strong impulse close to the ear – lasting a few ms – can cause such forms of injury, even in the absence of a high L_{EX}. Pattern recognition is also important for noise-induced damages in children [3], and related directives [8].

The complex structures of the human ear show vibrating patterns that depend heavily on frequencies [11], and natural frequencies of components are relevant [12,13]. Therefore the pressure-time-history of the acoustic stimulation is important. Impulse-related damages at a workplace indicates that the problem of impulses has to be addressed, and so pattern recognition is important for preventive activities. The best such action is to inform everyone about the danger of impulses close to the ear, so that he or she can take preventive activities. Since most harmful impulses can be foreseen, at normal workplaces and during hobby activities, such a strategy is highly effective.

Persons exposed to high levels of sound for some time have a reduced sensitivity of hearing afterwards. Temporary threshold shift (TTS) is said [1] to support the concept that the acoustic energy is most relevant for developing injury to hearing. However, this may not be so [5]. The auditory system, recognizing or anticipating extensive high sound levels, can apparently reduce the sensitivity of the ear to some extent, as demonstrated by referees and others. Our hearing system is a highly regulated functional arrangement that does not simply respond to the level of acoustic energy received.

At this point the danger presented by various types of impulses has to be evaluated. The auditory system in man is an under the influence of the auditory part of the nervous system. It is important how the energy of an impulse (or other signal) is applied to the vibrating system. In other words the pressure-time-history is relevant. In a thorough test of different evaluating procedures [14] it was shown that the AHAAH-procedure [10] has severe deficiencies. It overestimates the protective function of low frequencies and strongly underestimates the danger caused by very short impulses. Furthermore, according to this procedure, one blow of a referee whistle is declared to be much more harmful than a shot of an antitank weapon. Nevertheless referees using the very loud whistles for a decade hear very well. – This observation is of general interest. The auditory system of a referee knows when the whistle will be blown, and it apparently takes effective preventive measures. Similar conditions may apply to orchestra musicians, and others. Of course, all preventive actions of the ear itself have their limits. – Middle-ear muscles have no protective function. They suppress low frequencies and their masking effects on the important high frequencies, and so they act as a sort of auditory accommodation.

7 Conclusion

There are two independent harmful mechanisms – chronic degeneration due to long-term high noise-levels and acute acoustic trauma due to powerful impulses close to the ear. Rarely occurring impulses cause much more damage than continuous noise. They bring about four characteristic types of damage in the audiogram, depending on the pressure-time-history of the impulse. Pattern recognition, combined with high-quality audiometry, is very helpful. – The equal energy concept of ISO1999 cannot be validated.

8 References

[1] ISO1999 International Standard: Acoustics – "Determination of occupational noise exposure and estimation of noise-induced hearing impairment". 17p.; 2nd Ed. (1990).

[2] G. Fleischer, R. Müller "Auditory Group Curves – a powerful tool for analysis and prevention" Noise at work 2007; First European forum on effective solutions for managing occupational noise (Lille, France), 9 p. (2007).

[3] G. Fleischer, E. Hoffmann, R. Lang, E. Müller "Dokumentation der Auswirkungen von Kinderknallpistolen" (Effects of toy pistols) HNO 47; 535-540 (1998).

[4] G. Fleischer, R. Müller, T. Bache, G. Heppelmann "Auditory effects of some Millennium celebrations in Germany" Z. Audiologie, 42 (3), 106-116 (2003).

[5] G. Fleischer "The Intelligent Ear" Pro Acoustics, Schriftenreihe Vol. 1, 71 p.; ISBN 3-00-010642-1 (2002).

[6] A. Behar, W. Wong, H. Kunov "Risk of hearing loss in orchestra musicians" Med. Probl. Perform. Art **21**, 164-168 (2006).

[7] EU-Directive 2003/10/EC "On the minimum health and safety requirements regarding the exposure of workers to risks arising from physical agents (noise)." Directive 89/391/EEC (2003).

[8] CEN – European Standard EN71-1 "Safety of toys – Part 1 : Mechanical and physical properties" ICS 97.200.50 (1998).

[9] X. Niu, Y. Tahera, B. Canlon "Environmental enrichment to sound activities dopaminergic pathways in the auditory system", Physiology & Behavior 92, 34-39, (2007).

[10] R.G. Price "Validation of the auditory hazard assessment algorithm for the human with impulse noise data" J. Acoust. Soc. A. **122** (5), 2786-2802 (2007).

[11] S.M. Khanna, J. Tonndorf "Tympanic membrane vibrations in cats, studied by time-averaged holography" J. Acoust Soc. Am. 51; 1904-1920 (1972).

[12] S. Puria "Measurements of human middle-ear forward and reverse acoustics; Implications for acoustic emisssions" J. Acoust. Soc. Am. 113; 2773-2789 (2003).

[13] A. Eiber, C. Breuninger "Mechanical aspects in human hearing" Int. Design Engineering Technical Conf., Long Beach, CA. DET2005-84318 (2005).

[14] G. Fleischer, R. Müller "Evaluation of powerful acoustic impulses and their effect on the human ear" Symposium Acoustics in Defense (Meppen, Germany); 28 p. – ISBN 978-3-935938-44-0 (2007).