Amazing strategies of the ear against noise-induced damage versus ineffective concepts in auditory protection

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ABSTRACT

Fighting the noise-level of technical equipment was very successful during the last decades. Unfortunately, permanent auditory damage is still widespread, practically everywhere. In order to tackle this problem the Auditory Research Group at the Medical School of our university was systematically working on two types of methods, for more than two decades. A) Persons were examined who suffered from noisy events that damaged ear and hearing. In most cases it was possible to reenact the situation, to measure the damaging acoustic input, and to correlate the results with other data. B) Auditory performance of entire groups of persons were determined, such as orchestra musicians, construction workers, fire fighters, bureaucrats, airline pilots, nomadic people, blind persons, etc. Measurements were made, to obtain a rough idea of the acoustic environment of the various groups examined. - Currently the basis for auditory protection is the ISO 1999, stating that auditory damage is a function of higher long-term levels of acoustic energy in the environment. Our results do not confirm this energy- concept. Most harmful are acoustic impulses, and their pressure-time-history is the relevant factor. There are three main types of damage, and they are caused by resonances of middle ear components. These relations are very helpful for preventing noise-induced injuries, including tinnitus.

INTRODUCTION

After more than half a century of research related to auditory injury caused by noise, it is still necessary to collect accurate data. A lot of work has been devoted to this topic, Rüedi and Furrer(1946), Henderson et al(1976), Kryter(1977), Dancer et al.(1992), Axelsson et al (1996). According to the world-wide standard, ISO1999, it is assumed that the hearing system is a rather passive unit, that is primarily influenced by the long-term level of acoustic input. But there is growing evidence that the auditory system is not the passive device at all, but a highly active unit with a number of strategies for defence and survival.

METHODS

To learn more about it, our team let it be known that we are interested in persons who suffered from mishaps, accidents, or attacks involving powerful sound that caused permanent damage to hearing, including tinnitus. Not only adults came forward, but also many parents with a child that suffered from exposure to emissions from dangerous toys. All were questioned about education, job, hobbies and habits, and the supposedly harmful situation was determined thoroughly. The participants got a check up of the ears, and a tympanogram. If these persons had no prior experience with audiometry, they got a practical training so we could be sure that they were familiar with audiometry. To avoid problems with tinnitus, pulsed tones were used in

pure-tone audiometry and the validity of the audiogram was increased by means of retesting at random frequencies before the audiogram was accepted.

Details of the probably harmful event(s) were ascertained and recorded, including the surroundings, and, of course, the device or object that produced the harmful acoustic signals. With these data the events were reenacted in the laboratory, accurately, and the acoustic signals were determined with a special impulse-dummy (sampling rate 100kHz), and simultaneously with free-field microphones. A few events could not be reenacted, e.g. powerful explosions. Other measurements came to surprising results.

Another method was studying the auditory performance of entire groups of persons who share the same, or similar, acoustic environment. Construction workers, fans of discotheques, avoiders of discotheques, dentists, police officers, Tibetan monks in a remote monastery, etc. In these cases we took the technical equipment with us to the focal area of the groups to be examined. The studies in China were in cooperation with the Medical University in Xian. Collecting general and health-related aspects were the same as in the impulse part oft this study. All data were analyzed after being made anonymous.

RESULTS

First the persons who suffered from exceptional acoustic events. As can be expected, they were injured by impulses. Three typical notches are apparent, indicating different mechanisms, shown in Fig. 1. At low frequencies there can be a trough around 500Hz that is caused by resonance of the mastoid cells (mode A). These cells function as a muffler, with the form of a Helmholtz-resonator. Stimulated with strong low-frequency sound, they resonate. At higher frequencies (around 4 - 6 kHz) is the resonance of the entire stapes, pushed by the incus, it is moving hence and forth (mode B). There is another resonance of the stapes at around 12 - 14 kHz. Apparently the stirrup is ringing or tilting (mode C). All these resonances stimulate the cochlea excessively, and damage affects the hair cells.

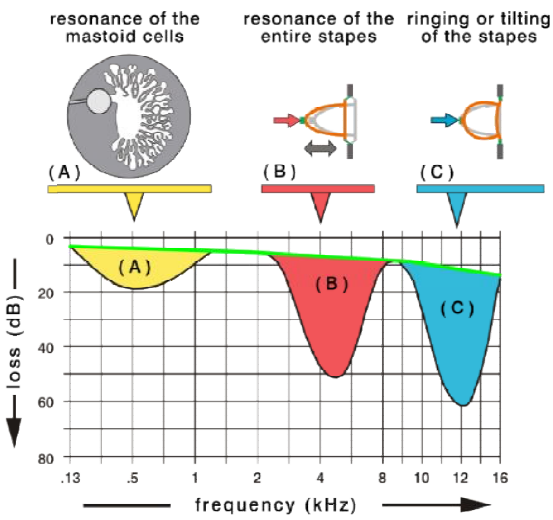

Figure 1: Effects of the three middle-ear resonances

Damage by impulses is in most cases associated with tinnitus. It starts immediately after the harmful event. Injury at high frequencies are particularly vulnerable for tinnitus, and in some cases the tinnitus is persisting lifelong.

Engineers dislike resonance because of non-linearity and the uncertainty. Nature, however, includes resonating structures into the sound conducting apparatus to gain increased sensitivity. Fig. 1 shows the footsteps of resonances. Such injury does not heal, hence it is possible to find in recent audiograms the footprints of an impulse that damaged the ear decades ago. The majority of hearing loss in technical societies can be attributed to impulses.

How do acoustic impulses stimulate these resonances? Key to understanding these relations is the pressure-time-history of impulses. In Fig. 2 some impulses are shown, along with their harmfulness for hearing. The pressure-time-history (PTH) of a driver-airbag has been C-weighted to suppress infrasound. It is a long signal, with a peak occurring rather early, and than fading down slowly. The free-field measurement was done at the place of the driver's head, and its peak is much higher than the permitted 0.2 kPa. Yet this sort of airbag is relatively harmless. The pin-anchoring device produces signals that are shorter and more harmful, but the shot of a blank pistol nearby is both, extremely short and extremely dangerous for the ear. One such impulse, lasting about 1 ms, can ruin the ear for life.

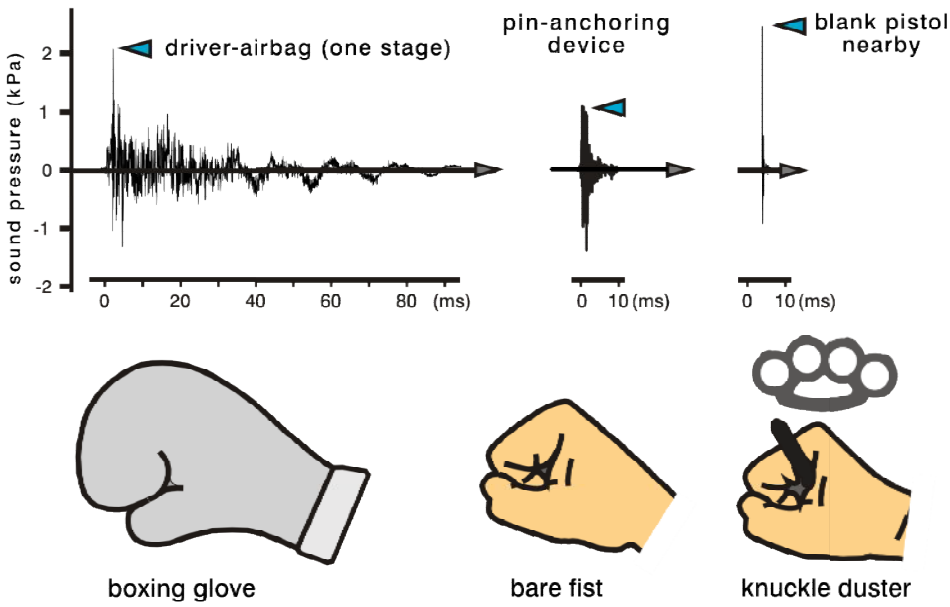

Figure 2: Pressure-time history of impulses

Hohmann favours measuring the energy content of an impulse for 1 s. In the USA a human ear model was developed (Price and Kalb(1998)) that uses the pressure-time-history of impulses, but it has severe deficiencies and will not be discussed.

Energy content does not explain Fig. 2. Inflation of the old-fashioned airbag forces much more energy into the ears of the driver than the dagger-like impulse emitted by

the blank pistol. But the airbag is harmless while the shot from the pistol is extremely damaging. Peak pressure is also not critical, particularly given the fact that the impulses from airbag and pistol are an order of magnitude higher than what is permitted at the workplace. The airbag weakly stimulates (mode A) while the shot strongly stimulates resonances of (mode C) und (mode B).

At this point the topic of masking has to be addressed. High frequencies are being masked by simultaneously present strong low frequencies (upward masking) Zwicker and Fastl(1999). Because the ear is much more vulnerable to high-frequency damage, this risk is reduced by the presence of strong low frequencies. Impulses, such as those from the inflating airbag, protect the ear against injury at high frequencies. However, the extremely short, impulse from the pistol, are amplified by the resonances (mode C) und (mode B) and forced into the cochlea.

Our hearing system has several strategies to fight noise-induced impairment, although this is not widely recognized. Being in a very loud environment for some time, the ear realizes it may be too loud, it reduces its sensitivity. Because it does not know how long this unhealthy stimulation will last, it returns to normal sensitivity only after some time. This is well known, and called temporary threshold shift (TTS). TTS is good for avoiding auditory impairment.

In case an ear got previously damaged by harmful acoustics - impulses or otherwise - another protective measure is applied. Apparently the person who's ear(s) have been damaged needs a warning. This is being done by lowering the threshold of pain. Persons with noise-induced damage quite often feel pain in the ear at loudness levels that are no problem for healthy ears. This method of the damaged ear - hyperacusis - is also a good procedure to prevent further damage.

Middle ear muscles have no protective effect for hearing. They suppress low frequencies that would otherwise impede the perception of high frequencies. It is their function to improve hearing high frequencies in the presence of low-frequency noise.

At this point it is necessary to emphasize a basic principle that is, unfortunately widely ignored in auditory protection. For reenacting a harmful acoustic event it is essential to use the same distance between the origin of an impulse and the microphone, or impulse dummy. And the environment around the head of the affected person must also be copied as exactly as possible. In this way reflexions can be included that increase the sound level at the ear. - For selling technical equipment it is useful to indicate the noise level at a standard distance. However, in auditory protection all that counts is the real distance between the origin of an impulse and the affected ear(s), Fig. 3. If a source of an impulse is very close to the ear, something like 1 cm (0.4") the result is dramatic. A child is using a little plastic toy horn so close to the ear of another child. The affected ear has to pick up an impulse that can have the same level as that of an ear at arm's length from the horn of a big fire engine.

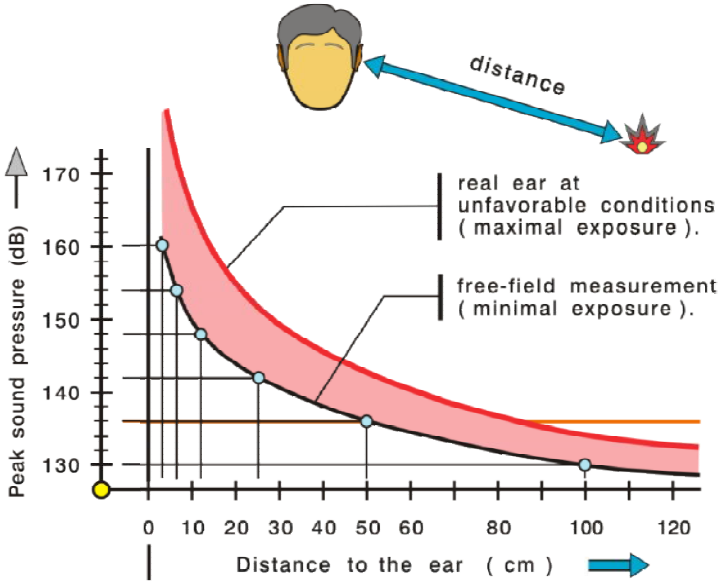

Figure 3: Distance between ear and origin of impulse

Now entire groups of persons are the topic of interest. Comparing groups is troublesome because normally they differ in number and age of the individuals. What is necessary is a method that is independent of the age of the individuals. For this purpose the Auditory Group Curves were developed by our team, Fleischer et al(2005). The basis is a semi-schematic overview of normal aging, based on several thousand audiograms of persons without apparent auditory impairment, living in central Europe. These age-lines are shown in Fig. 4. By electronic intercalation age-lines were established for a yearly basis, from 18 to 70 years. After taking audiograms, the computer program compares it with the corresponding age-line of the individual. The program combines all age-lines to a straight horizontal line for "normal aging". Deviation from the individual age-line is then treated as deviation from the horizontal line for normal aging. The curved age-lines have been replaced by a horizontal line, omitting the influence of different age.

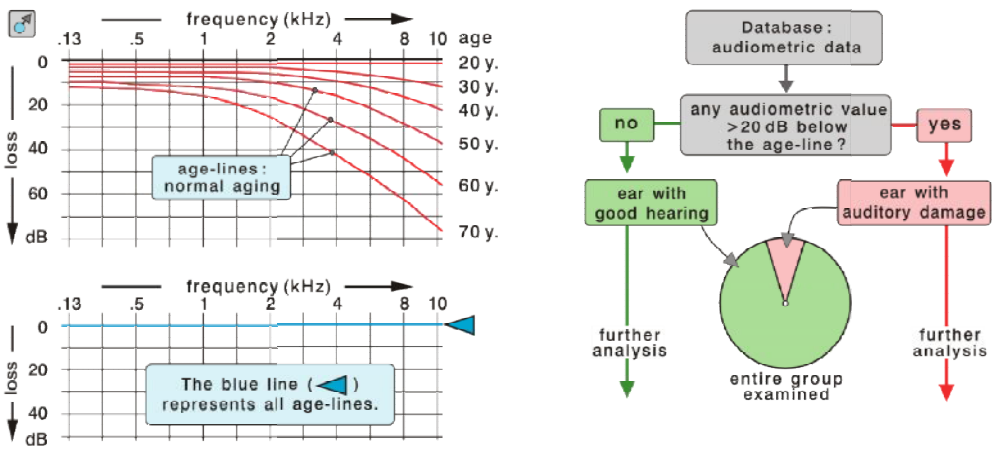

Figure 4: Basis for auditory group curves

Now it is necessary to define what is "normal" and what is called "auditory impairment". It was decided to accept a variation of 20dB around the corresponding age-line. In other words: if one or several audiometric values is more than 20dB below the corresponding age-line the ear is declared to have "auditory damage". This

means also that an ear with an audiogram where no audiometric values are more than 20db below the corresponding age-line is "hearing good". All this is being done by computer. The program automatically separates ears with good hearing from those with auditory damage. Both types of data are available for further analysis. - In case it is desirable for special purposes, the criteria for good hearing and auditory damage can be modified easily.

An example of Auditory Group Curves is shown in Fig. 5 left. It shows the auditory performance of 187 male professional orchestra musicians, left ear. At the audiometry date their age was between 21 and 70 years. Normal aging is represented by the horizontal blue line. 83% of these ears hear good: no audiometric value >20dB below the corresponding age-line. The green line refers to good-hearing ears and the group curve values show less aging than normal for all frequencies above 250 Hz. The black line shows all ears put together, hence without separating between good-hearing and damaged ears. The red line refers to the 17% of the ears with damage. As expected, they have a loss compared to normal aging, that increases from low to high frequencies. Orchestra musicians hear better than normal.

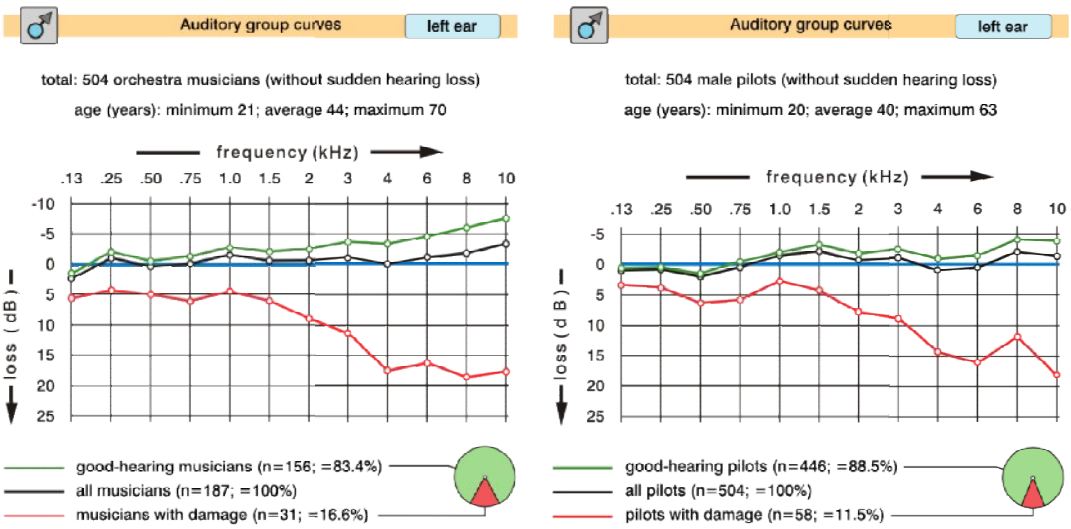

Figure 5: Auditory group curves, musicians vs pilots

On the right side of Fig. 5 are Group Curves from 504 airline pilots. It is interesting to look at those with auditory damage, red line. There is a trough around 500Hz, indicating to resonance of (type A), and another at about 6kH, indicating to resonance of (type B). This red line is a summary of 58 pilot ears with damage, 11.5% of the entire group.

Which groups have the best sense of hearing? The effects of accidents, mishaps, etc. are not relevant for this task, and therefore only those data of the group curves are used that refer to ears without damage. In other words: the audiometric values of the green lines in Fig. 5 are used for the comparison of different groups of persons. Values above the horizontal (blue) line for normal aging indicate hearing threshold better than normal, and those below the blue line indicate a threshold worse than normal. For every group of persons, the program determines how much the audiometric values are, on average, above or below normal hearing.

An overview of the ranking is presented in Fig. 6, but at the lower part a number of groups have been omitted for the sake of simplicity. Orchestra musicians and airline pilots have already been discussed. Students in college or university who have never been to a discotheque (disco avoiders) hear a little worse than normal, and 9% have auditory damage. Those who visit discotheques regularly (disco fans) hear only minimally worse and 10% have auditory damage. Construction workers in Germany, using heavy machinery, hear very bad, and 54% show auditory damage.

Nomadic people in Qing-Hai province of China are a special case. Everything indicates that they suffer from auditory deprivation. They are not hearing good, their hearing system may not get the training to keep in good shape. Aging begins early, especially in men, and it progresses rapidly.

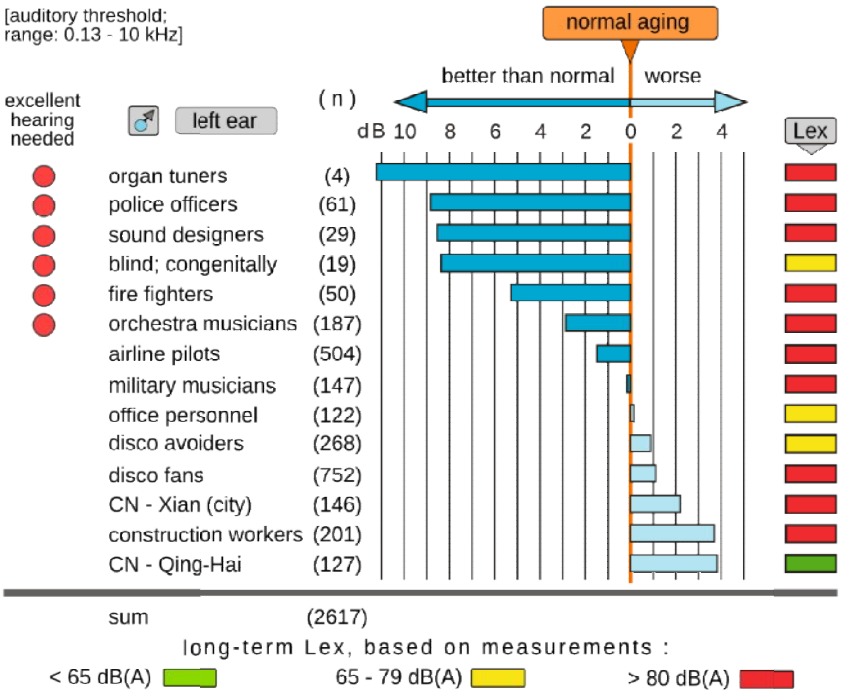

Figure 6: Ranking of good-hearing groups of persons

In Fig. 6 the long-term sound level of the environment is indicated. Organ tuners are working at long-term Lex of more than 90dB. Sound designers and orchestra musicians are said to be affected by high sound levels. Fire fighters are famous for working in an extremely noisy environment, yet they hear excellent. Congenitally blind persons avoid noise and they do hear marvelously well. Studying their hearing indicates that pure-tone audiometry may not be optimal for fully determining their acute sense of hearing.

To understand the sense of hearing in various groups it is necessary to learn as much as possible about their daily work, their efforts and their problems. Orchestra musicians and sound designers desperately want to perform excellently, and that is the centre of their lives. Organ tuners demonstrate acoustic details that the author could not confirm for lack of training. Fire fighters need excellent hearing to save the

life of other people and their own, and they depend on acute hearing. Police on the beat have a dangerous job, particularly at night, and so they have to control the area behind them to some extent by the ear. Congenitally blind persons mostly use the echo of the noisy environment for orientation, and it is overwhelmingly impressive how much they can hear.

CONCLUSION

Auditory performance is subject to training in various ways, much like other systems of the human body. Most harmful for the ear are powerful impulses. Their energy content is not primarily relevant, but the pressure-time-history is. Particularly harmful are very short (dagger-like) impulses.

For effective prevention of noise-induced damage it is necessary to inform the public about the harmfulness of acoustic impulses, especially close to the ear. Since about 90% of harmful impulses can be foreseen, everyone should know how to protect the ears or simply go away from the dangerous area. Damage of the ear due to noise is not an acoustic problem, but a lack of basic information.

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