Acoustics versus insight: Strategies against noise-induced auditory damages

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INTRODUCTION

For two decades our team is working intensively on the relation between auditory performance and acoustic environment. This is being done using two different approaches. One is the basis for our **archive of acoustic impulses**. All sorts of acoustic events are being collected, that caused noise-induced auditory damage. The victims come to us, or they are referred to us by ENT specialists. These persons get a thorough inspection of the ear, plus tympanometry and pure-tone audiometry from 125 Hz to 16 kHz. Pulsed tones are being used for easy recognition. Everyone gets a detailed questionnaire, related to everything around ear and hearing, including tinnitus. The damaging event itself is handled next. It is important to know exactly what caused the harmful acoustic emission, how far it was from the ear(s), along with details about the environment at the time. In most cases it is possible to re-create these conditions and measure the resulting acoustic emission. For this purpose we use a special impulse-dummy that can handle pressure peaks up to 188 dB. Simultaneously a free-field microphone attached to the outside of the dummy is also used. In both cases – dummy and external microphone – the pressure-time-history of the event is recorded with a sampling rate of 100 kHz. The collection contains data on persons from the age of 6 years to 70 years. All our audiometric data on injury of hearing refer to permanent threshold shift (PTS). In other words, we are not involved in experiments on temporary threshold shift (TTS). Harmful objects examined include toys for children, machinery at workplaces, airbags, and weapons, all the way up to tanks and howitzers.

Everyone knows that occupational noise varies enormously among the many different types of jobs. In order to find out how this affects the sense of hearing we were (and are) studying entire groups of persons, as completely as possible. There is – and was – no selection of persons. Such an approach has the advantage that a number of persons are being examined that have never been patients of ENT experts. Studying entire groups of persons is **the other major procedure**. Among those groups examined are construction workers, office personnel, fire fighters, police officers, orchestra musicians, sound designers, airline pilots, school children of various age, congenitally blind persons, fans as well as avoiders of discotheques, Tibetan monks, nomadic people and mountain-dwellers in remote parts of China that are not exposed to technical noise. All these persons participated voluntarily, they got a thorough inspection of the ears, a detailed questionnaire, and a training session in audiometry, before undergoing the audiometric measurement that is being used for comparative analysis of the results.

To compare various groups directly, a new analytical technique had to be developed that enables comparison of audiograms of entire groups of persons, independent from the age of its individuals. The result of our technique is called “**auditory group curves**”, and an overview is presented in Fleischer and Müller (2007a). Its basic concept is to compare the audiogram of an individual not with the auditory threshold of young adults, as usual. Instead, the individual´s audiogram is compared to those of persons of the same age, with normal aging of the ear. With such a procedure it is possible to compare different groups of persons directly, independent from the size of the groups, and the age of the persons in both groups. Ranking of different groups can be worked out, regarding the quality of the auditory threshold, as well as the occurrence and severity of auditory damage.

CONTINUOUS NOISE

Apparent and widespread damage to the sense of hearing during the second world war boosted research in the field of noise-induced auditory damage, and it started in earnest with the extensive study by Rüedi and Furrer (1946). A large number of experimental studies followed, applying a bewildering array of different types of acoustic exposures of various experimental animals. More than half a century ago Eldred et al. (1955) created the **equal-energy-concept**, stating that it is the long-term amount of acoustic energy reaching the ear that is causing permanent injury to hearing. Furthermore, the same amount of acoustic energy is said to cause the same amount of damage. More details in Henderson et al. (1976). At the time this was a great progress, making studies and preventive activities comparable and understandable. This principle later became the basis for the world-wide noise-standard ISO 1999, as well as a large number of concepts and activities. In fact, some modifications not withstanding, it still is the basis for protecting the ear against harmful noise at the workplace, **Figure 1**.

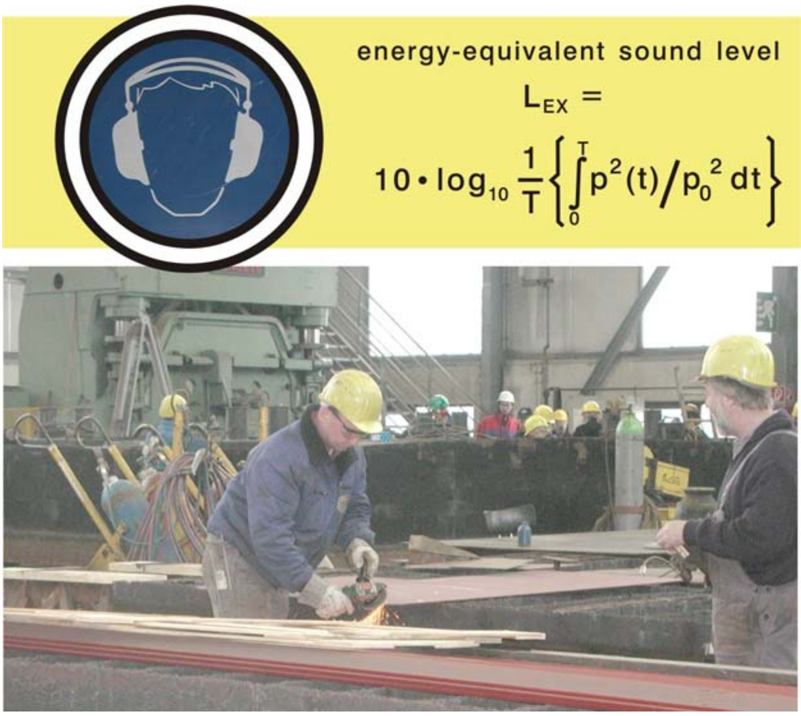

Figure 1: Evaluation of continuous noise

After exposure to high noise-levels – at the workplace or in a discotheque – the ear is less sensitive, because of temporary threshold shift (TTS). According to the energy principle the TTS is an injury that can heal relatively fast, but over time this healing process is said to become slower and slower, and finally remaining permanently (PTS). Hence, TTS is declared a negative phenomenon. However, the auditory system is an enormously complex and highly regulated functional component. If it recognizes that the sound level it is exposed to is too high, it reduces its sensitivity. As a result, TTS is a sign of protective activities of the auditory system, and it can be regarded as a positive phenomenon.

IMPULSES

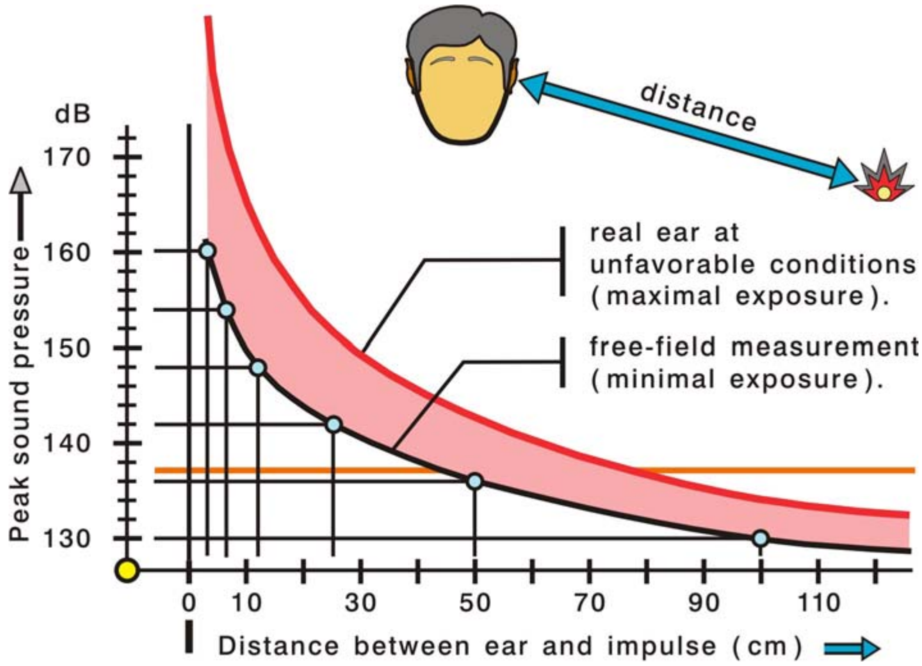

Figure 2: Influence of the distance between ear and impulse

Analysing damages to the ear, caused by powerful impulses, reveals that there is one parameter that is much more prominent than the others. It is the **distance between the source of the impulse and the ear(s)**, **Figure 2**. If only a microphone is present – as in free-field measurements – peak sound pressure increases systematically and predictable as the distance between impulse and ear decreases. If a human being is present, the pinna, the outer acoustic meatus, as well as the middle ear modify and increase the signal. There is a further increase due to reflections, especially in narrow spaces. Such relations are not new, of course, but they are widely ignored, at the workplace and elsewhere. It is apparent that impulses that are harmless at arm´s length, can be extremely harmful very close to the ear. Free-field measurements cannot be directly compared to measurements by an impulse dummy, but dummies are very helpful to realistically determine the danger caused by impulses close to the ear. – The brown horizontal line in Figure 2 indicates the maximal peak allowed for the unprotected ear, according to the EU-Directive 2003/10. Sound sources very close to the ear are especially harmful, but the European standard for the safety of toys – CEN(1998) – does not seem to care about this at all.

A survey of the harmful impulses in our database reveals four basic **damage-patterns in the audiogram**, **Figure 3**. According to our analysis the types (A), (B), (C) are the result of resonances within the middle ear. Damage of type (A) is caused by impulses with powerful low-frequency impulses, such as shots of heavy weapons near by (in connection with type (D)), or a collision of big objects, such as an excavator hitting the cargo unit of a heavy truck. Type (B) is the well-known c5 notch, represented primarily by resonance of the entire stapes. Type (C) is caused by “ringing” or “tilting” by the stapes, stimulated by extremely short impulses – lasting only a fraction of a milli-second. In such cases the distance between impulse and ear is always less than one meter. The last of these forms of damage is type (D). It is the result of a massive impulse, the pressure of which is rising extremely rapid. As far as we can see, there is a non-linear destructive wave running into the cochlea causing massive damage, and loosing its power at lower frequencies, higher up in the cochlea.

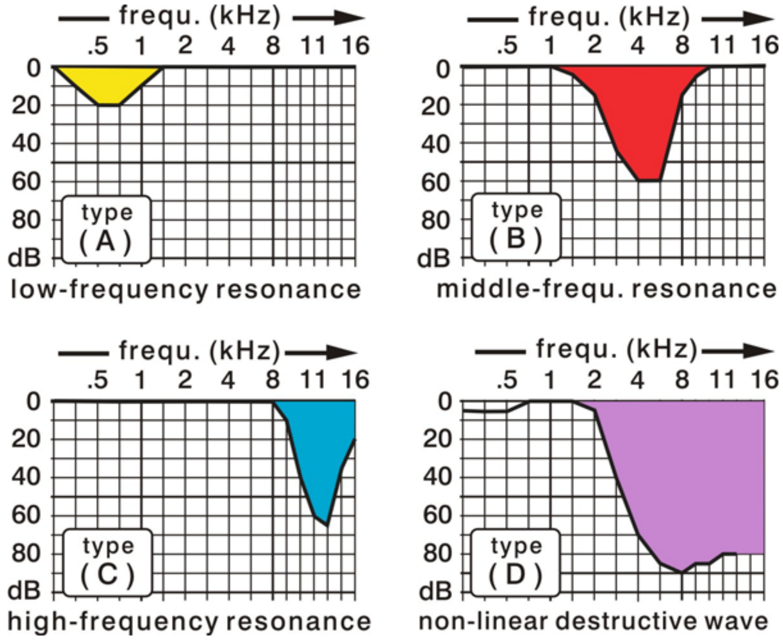

Figure 3: Typical damage patterns of powerful impulses

These basic types of damage are the footprints of powerful impulses. If such a pattern shows up, one single impulse can have caused such harm, or a few of them. But such patterns do not appear as a result of long-lasting high sound levels. Strong impulses produce a damaging mechanism of their own. If such forms of damage are apparent, it is not relevant to determine the long-term level of acoustic energy. Of course, such patterns can only be detected if many frequencies are being tested during audiometry. The frequencies declared relevant by the ISO 1999 noise standard are definitely <u>not</u> sufficient to use the modern tool of pattern recognition.

Functional details of the ear have long been known as highly non-linear (Khanna & Tonndorf 1972; Eiber & Breuninger 2005) and many others. They are an indicator that the mode of stimulating the ear is more important than the simple energy content or the peak pressure.

After a long time for development the Human Auditory Hazard Assessment Algorithm (Human AHAAH) was explained to the public (Price 2007). It shall evaluate the risk to the ear, presented by impulses. Characteristic damage patterns are not shown, and it appears to have serious systematic deficiencies, as shown by a thorough test (Fleischer & Müller 2007b). According to the AHAAH procedure, probably the most dangerous device for the ear appears to be the widely used referee whistle, despite the fact that referees are hearing well.

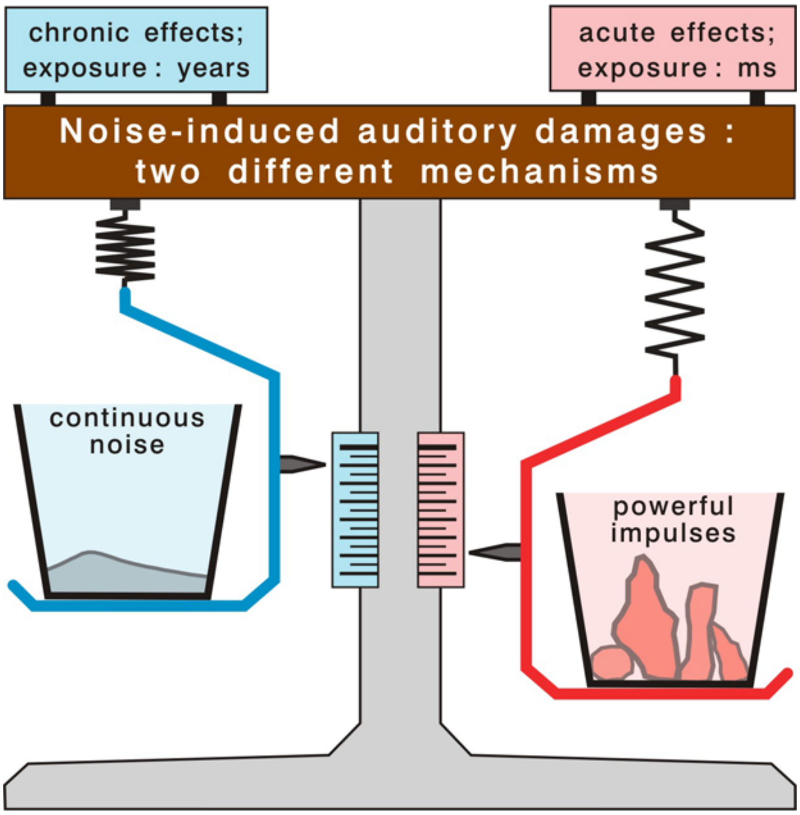

Figure 4: Continuous noise compared to strong impulses

Combining all our experience – based on two decades of detailed work, covering data on roughly 11,000 persons – it can be summarised in one illustration, **Figure 4**. There are different mechanisms for noise-induced damage: continuous noise is wearing down the cochlea after years or even decades. Strong impulses can massively damage the ear after exposure time of a fraction of a second. Quite often it takes only less than one thousands of a second for an impulse to ruin the ear. As far as shots or impulses are concerned the equal-energy-concept is simply invalid. The pressure-time-history is the relevant signal, and that is why this sort of signal should be recorded and analysed thoroughly. Peak-pressure is less relevant for evaluation of the danger caused by impulses.

It is important to notice that a single impulse can seriously damage the ear, even in total absence of loud continuous noise (Fleischer 2002). At the workplace it is important to recognize that damage caused by an impulse can easily occur even under conditions with an L_{EX} well below 80 dB(A). The common practice to deny that noise-induced auditory damage at the workplace can occur at such low sound levels ignores the harmful effects of impulses. A strong impulse, lasting just one millisecond, can permanently ruin the ear. Such rare, harmful events, shall not be declared as atypical, and otherwise ignored.

DIDACTIC PRINCIPLES

The equal-energy-concept means that the ear is basically functioning like an ancient grindstone. While steel is being ground, the grindstone itself is slowly but unavoidably being worn down. Hence, the best you can do for the grindstone is not to grind steel. According to traditional thinking, along the lines of the **equal-energy-concept**, sound – especially if it is loud – is slowly wearing down the ear. So the best you can do for the ear is to generally protect it from sound. Therefore, it is assumed that people living in remote areas under conditions without technical noise are hearing excellent, up to high age. However, this is not so (Fleischer 2002). One reason certainly is that the auditory system – like other systems of our body – need training to fully develop its functional capabilities in childhood, and to keep in good shape thereafter. People living in an environment of very little sound (e.g. nomads) suffer from auditory deprivation.

Returning to damages, caused by noise. This is basically not an acoustic problem. Noise-induced damage is not most widespread where the noise is most powerful, but it is very prominent where the persons are the most ignorant. Hence, improving knowledge and insight are extremely effective in preventing damage to the ear.

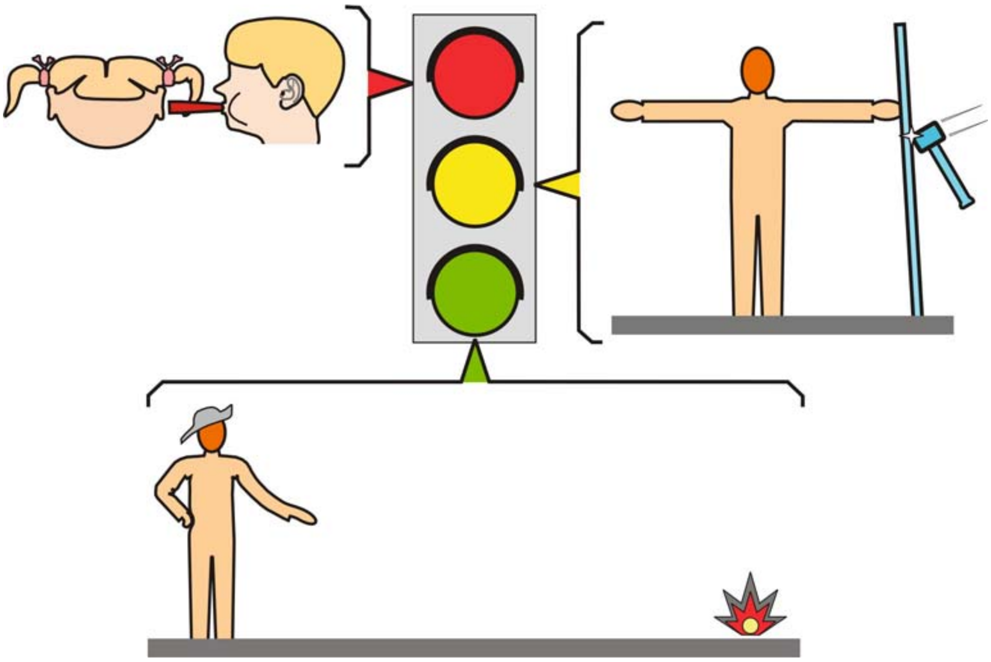

Figure 5: Keeping loud sound sources away from the ear is the most effective preventive measure

Arguing with formulae and decibels is an exercise in frustration. But experience shows that even young schoolchildren easily understand that it is of utmost importance to keep loud objects and events away from the ear, **Figure 5**. Such an approach is particularly effective because the person learns to be alert and to take care of his or her own health. This knowledge is available not only at school or workplace, but any time and everywhere. And it can easily be passed on to family and friends.

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