5aNSb4. Evaluating harmful acoustic impulses

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Noise-induced auditory impairment is widespread, despite many successful efforts to reduce sound emitted by technical equipment. Using accumulated acoustic energy as an indicator for health hazard, as in ISO1999, is insufficient to describe the hazard for impulses. While stimulating a system with many vibrating parts, like the ear, it is more important how the energy is fed into the various components than how much is applied. The Human Ear Model (AHAAH) uses the pressure-time-history of impulses which is much better. It is based on theoretical assumptions, but it has serious deficits that lead to results that can be extremely wrong. Within another long-term approach the effects on hearing of accidents caused by impulses have been collected and documented. The harmful situations were reenacted thoroughly, to obtain acoustic measurements that can be correlated with the auditory damage, if present. All told, impulses cause three types of notches, at different frequency ranges. Hence, harmful impulses show characteristic footprints in carefully recorded audiograms, and the type of notch depends upon details of the causing impulse. This EPI approach (Effects of Powerful Impulses) applies to most cases of auditory damage, and it is useful to prevent and understand such injuries.
ISO1999

To prevent noise-induced injury to hearing the standard ISO1999 has been established, and it is being applied practically everywhere.[ISO (1990)] It postulates that if the ear is exposed to more long-term acoustical energy the likelihood increases that it will suffer permanent injury. Hence, the long-term level of acoustic energy picked up by the ear has to be limited. This concept is convincing and straightforward, and lots of technical equipment has been developed that emits much less noise than before. However, noise-induced damage to the ear is still very widespread. What’s wrong? This ISO standard ignores basic structures of the ear. Our ear is a complex system, with a number of resonating components. For stimulation of such a system, it is not primarily important how much energy is being fed into it, but how the energy is applied. These aspects are particularly important for impulses, but they are practically ignored. As far as the relation between exposure and damage is concerned this standard attributes all negative (or positive) effects to the total energy absorbed by the ear.

AUDITORY HAZARD ASSESSMENT ALGORITHM FOR HUMANS (AHAAH)

This mathematical model, developed by Price and Kalb, uses the pressure-time-history (PTH) of acoustic signals as input that is analyzed by a computer program [Price, R.G., Kalb, J.T. (1998), Price, R.G. (2005)]. Using the PTH of impulses is a good improvement on ISO1999 because it offers the possibility to evaluate the specific details of every impulse on structures of the ear. The model represents middle ear and cochlea, including the traveling waves, but no details appear to be available how this is being done. Analyzing acoustic events results in Auditory Risk Units (ARU), numeric values that are supposed to indicate how harmful (or harmless) such a signal would be for the ear. Risk units can be accumulated. This model was originally developed for impulses from weapons, but later it was called Human Ear Model, applicable to all acoustic signals. Human audiometry for the development was modest, using apparently just frequencies from 500 Hz to 8 kHz. Probably because of such narrow audiometric input, important effects were missed, and mistakes occurred. The AHAAH-model distinguishes between hearing an impulse “unwarned” and a “warned” condition, when a loud signal preceding the impulse is supposed to stimulate the middle-ear muscles, thereby diminishing the following impulse. Discussion below.

EPI APPROACH

Both ISO1999 and AHAAH are based on theoretical concepts of ear and hearing. But there is a third concept - the EPI approach (Effects of Powerful Impulses), based primarily on observation and experience. The Auditory Research Group at Justus-Liebig-University in Giessen, Germany, systematically collected data related to hearing in general, and noise-induced damage in particular, for about two decades. No experiments were involved. All participants volunteered and they were interviewed about age, education, job, military service, hobbies, including consumption of music etc, general health, and problems related to ear and hearing. We asked whether they recall forceful acoustic event(s). If necessary, all persons got some training in audiometry, and then a pure-tone audiogram from 125 Hz up to 16 kHz was made, complete with random frequency checks, to assure accuracy.

Way of life

In order to learn how persons with special professions, or way of life, are hearing we organized situations were we could find many such persons (construction workers e.g.), asking them to cooperate with a questionnaire and get an accurate audiogram, also from 125 Hz to 16 kHz. Some groups examined shall be named here: orchestra musicians, civil airline pilots, young people who visit discotheques regularly, and those who have never visited a discotheque, police officers on the beat, dentists, professional firefighters, office personnel, congenitally blind persons, nomadic people without technical noise, Tibetan monks in a remote monastery, etc. Applying auditory group curves enables a comparison of auditory thresholds of entire
The best performance show organ tuners who work at levels above 90 dB(A) while the worst hearing have nomadic people in remote parts of China who are practically not exposed to technical noise. It is clear that the best performing groups depend on good hearing for safety and success. Nomadic people do not hear well, because of auditory deprivation. Apparently the ISO1999 dictum: lower long-term sound level = better hearing cannot be confirmed at all.

Harmful impulses

We let it be known that we are studying the effects of acoustic impulses, and persons affected came to the lab, or parents brought their child. Besides questionnaire and audiometry they were asked about the possibly harmful acoustic event(s) in detail. These events were carefully reenacted for detailed acoustic measurements: PTH (free-field, as well as specialized impulse-dummy). Harmful impulses emanated from children’s toys, fire engines, heavy military weapons, etc.
Analyzing the data collected about harmful impulses reveals three main types of damage, Fig. 2, that are based on resonances. Type A is a Helmholtz resonator, type B is vibration of the entire stapes, and type C is ringing of the stapes. To find these troughs it is essential to have detailed and thorough audiometry from 125 Hz to 16 kHz. Mastoid cells are designed to suppress resonance and therefore damage of type A is typically a wide, shallow trough. Ringing of the stapes (type C) can be relatively narrow, but it is nevertheless important for causing tinnitus that can be very massive and permanent.

**Figure 2:** The three typical types of damage caused by impulses, along with the damaging mechanism

**Figure 3:** Typical steps of increasing severity of impairment
Depending on PTH of a harmful impulse, the damage in the audiogram can show more than one type, Fig. 3. An impulse can cause moderate damage of type B. Another, more severe one, brought about damage of types A, B, and C. The low frequencies necessary to create type A trough can come from resonances within the environment of the affected person. An impulse that is extremely massive quite often creates very severe damage, characterized by type A plus the low-frequency slope of type B. Very short impulses lack the low-frequency components that are necessary to stimulate damage of type A. Severe damage starts very likely with a destructive, nonlinear wave at the base of the cochlea.

Comparing the PTH of different impulses reveals great differences, when presented in the same coordinate system, Fig. 4. (Infrasound has been suppressed by C-weighting). Modern driver-airbags are rather harmless, it takes a few ms to arrive at the pressure-peak, and there are strong low-frequency components that suppress the dangerous higher frequencies. However, a shot with the blank pistol is extremely short, its pressure takes only a small fraction of a ms to go to the peak, and the impulse contains no low-frequency components lasting long enough for masking the higher frequencies. One such impulse, originating at a distance of 20 to 30 cm, can ruin the ear for life. In the audiogram the injury to hearing is similar to "very severe damage" in Fig. 3, but without the low-frequency trough, type A. The energy content of the impulse from an inflating airbag (Lex8h=89dBlin) is ten times as high than that from the blank pistol (Lex8h=79dBlin). Energy content is not expressive for understanding injury to hearing caused by acoustic impulses. The Human Ear Model (AHAHH) is also not able to indicate one such very short impulse as extremely harmful. - In Fig. 4 these enormous differences in harmfulness are visualized below, from boxing glove to knuckle duster.

An old problem must be discussed briefly: What is the function of the middle-ear muscles? Tensor tympani muscle and stapedial muscle both act upon the ossicular chain, and hence many authors assume that the muscles help to protect the ear against harmful noise. However, these muscles are weak in man and fatigue starts early, what is not favorable for a protective function in an environment that is often very noisy for many hours. Furthermore, these tiny muscles reduce the transmission of vibrations to the cochlea only at low frequencies, below 1 kHz [Rabinowitz, W.R. (1977), Rosovski, J.J., Relkin, E.M. (2001)]. Since the human ear is most vulnerable in the frequency range between about 4 - 6 kHz, the muscles will not protect the ear against noise-induced injury. But the Human Ear Model contains a simulation of a protective function of the middle-ear muscles. If the ear is stimulated shortly before a potentially harmful impulse, the ear is declared to be forewarned and the program assumes a certain protective effect.
The function of middle-ear muscles becomes apparent from the aspect of masking. Driving leisurely through a pretty countryside in summer you can occasionally see a fox on a meadow trying to catch a mouse. Unfortunately, the low frequencies emanating from your car (or wind) are masking the high frequencies of the squeaking mouse. Contraction of the middle-ear muscles suppresses the disturbing low frequencies from the car so that the fox can hear, locate and catch the mouse. This mechanism is presented in Fig. 5. It is based on the fact that atmospheric attenuation of low frequencies is small so that they can be heard at large distance. High frequencies, however, suffer a high attenuation, and can only be heard at small distances. But they carry much information, and its source can be accurately located. Our visual system also needs to change from a "far" mode to a "near" mode. If you look at the fox you are focusing on an object that is far away. In order to tell this observation to your family, accurately, you look at the wristwatch, and your visual system is changing to the "near" mode; it is accommodating. Hence, the function of the middle-ear muscles is auditory accommodation.

Other failures of the Human Ear Model are its inability to detect or explain the damage-types A and C, presented in Fig. 2. It massively underrates isolated short, nail-like impulses, such as the shot of the blank pistol, shown in Fig. 4. But if there is a series of very short signals, this impulse is grossly overrated. According to our experience with this model, the referee whistle is evaluated by the AHAAH to be incredibly harmful to the ear, but referees who are using such modern whistles quite often, for many years, are hearing good. Apparently, there are systematic errors within this mathematical model.

**FIGURE 5:** Auditory accommodation is the task of the middle-ear muscles.

**FIGURE 6:** Hyperacusis and temporary threshold shift (TTS) are stratetic tools for preventing deterioration of hearing.
Working with people who have been harmed by acoustic event(s), show hyperacusis quite often. The auditory system lowered their threshold of pain. In sound designers or organ tuners the auditory system has been trained to handle such conditions so that no lowering of the threshold results. Hyperacusis is a way of the auditory system to warn persons damaged by sound to avoid loud environments, Fig. 6. Temporary threshold shift appears so be of similar nature. The auditory system recognizes potentially harmful acoustic conditions and gradually reduces the sensitivity of hearing, known as TTS. After being harmed by sound the neural part of the ear orders a recovery period for components engaged in handling weak signals, among them outer hair cells.

There is good evidence that the ear can reduce its sensitivity if it anticipates a potentially harmful impulse, such as a massive hammer blow. In referees the ears know when they will be affected by an impulse from the whistle. As an emergency program a “survival mode” appears to exist, capable of rendering the ear utmost insensitive within a small fraction of a second. It is activated e.g. if a firefighter, polishing the fire engine, is unexpectedly exposed to the blaring siren just 20 cm from his head. These and other reactions are subject to training effects related to impulses. Training, of course, depends upon the normal way of life, and can vary enormously.

**RECOMMENDATIONS**

By applying high-quality audiometry, damage caused by impulses can be recognized. An estimated 75% of all noise-induced impairment is caused by rarely occurring impulses. People should be informed how dangerous an acoustic impulse can be, and how easy it is to avoid most of them, because they can be anticipated. Experience shows that children in preschool easily understand the message and are proud to apply this knowledge. Such participation, at or outside the workplace, helps avoiding hearing impairment as well as tinnitus.

**SUMMARY**

ISO1999 is not suited to evaluate rarely occurring harmful impulses, and AHAH's mathematical model has serious flaws and misconceptions. The EPI approach involves impulses of all origins, and focuses on collecting detailed information on acoustic events, that have been (or may be) harmful. It shows a relationship between the structure of the impulse and the resulting type of impairment, enabling automatic screening. Very short impulses are much more harmful that currently assumed.

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