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Evaluation of the time and the time/frequency structure of handgun noise as a basis for hearing loss prevention in sport shooters

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Abstract: Background and aim: it is well known that weapon noise poses a risk on the hearing organ of sport shooters. Disappointingly there are no uniform criteria for evaluation of shooting ranges' acoustic environment. We aimed at presenting a method for an objective assessment of noise exposure in shooting sports. Materials and methods: we collected and described acoustic signals during training and competition in the 25 m shooting range. The recorded material was analysed with the orthogonal, adaptive parametrization by Shur. Results: the noise reaching the hearing organ of a shooter is combined of random, short-term, impulse-type signals emitted by weapon. We have found that among parameters required for the description of the shooting noise are: the effective duration of a specific signal, the time-domain structure of a combined signal, the time/frequency structure, the energy evaluation and the number of signals. Methods used for occupational noise evaluation are not appropriate for sport shooting because of differences of time and frequency characteristics of acoustic impulses. Conclusions: the orthogonal, adaptive parametrization by Shur recognizes the time-domain and the power spectrum of acoustic signals. It delivers adequate information on the hazard from the impulse noise in shooting sports.

Key words: weapon, sports, noise-induced hearing loss, impulse noise, noise evaluation.

Background and aim

Noise excess is a threat not only in occupational environment, but also during exercise and leisure. There is no rehabilitation for persistent hearing loss. The only method to avoid ear disturbances is prophylaxis based on proper monitoring of noise exposure.

Predicting the health-hazard associated with the exposure to the impulse noise emitted by weapon is difficult [1]. Several evaluation methods have been developed and they can be applied for military and occupational environments [2-8].

An intense impulse noise induces a damage to the middle and the inner ear [3, 7]. Auditory consequences depend on: the sound level, the duration and the number of impulses and an individual susceptibility as well [1, 9].

A number of criteria have been proposed to evaluate the auditory damage risk. Among these are: the iso-energy principle (the sound peak pressure, the duration and the number of the impulses) [9], the measurements based on the A-weighted energy [3] and the AHAAH model to analyze the weapon noise exposure of the human ear [1, 6, 10].

Shooting sport is characterized by a specific acoustic environment. Sport shooters are exposed to 100-200 acoustic impulses during a single training session. The amount of noise is multiplied by the number of simultaneously exercising sportsmen. Professional sport shooters may be exposed to as many as 100-1350 acoustic signals during a training unit (90 minutes) and about 200 000 acoustic stimuli in a year- long training macrocycle [11]. None of the existing standards to rate/evaluate the impulse noise is accurate for sport shooters.

Another problem is that sport shooters are not sufficiently protected against hearing trauma and they do not undergo proper audiological screening [12, 13]. Furthermore, the sport shooting rules exclude the use of silencers [14].

Although it is well documented that weapon noise is harmful to the hearing organ [15-21] there are no universal criteria for evaluation of this specific acoustic environment [2, 22-24]. Criteria used for the evaluation of the occupational noise exposure do not involve parameters specific for shooting ranges [22, 25-27]. Approaches such as the peak level method or the energy evaluation method have serious limitations. Their application is hindered by: differences of the time/frequency characteristics of recurrent impulses and an inadequacy of the equal energy principle in modeling risks for the hearing organ [22, 25-28]. Because of the specificity of impulse signals they cannot be analysed according to criteria routinely used for continuous noise [4, 29, 30]. Therefore it is also difficult to choose appropriate hearing protection devices (HPDs) for sport shooters.

A complete description of shooters' exposure should comprise: the type of a discipline, the signal's peak acoustic pressure, the spectrum (bandwidth), the duration, the energy level and the frequency of repetition.

Our objective was to propose criteria for evaluation of the weapon noise in sport shooters.

Materials and methods

In our investigation we analysed the noise exposure in the 25 m range. Records were made for several types of weapon and ammunition. Among them were pistols: .22LR Baikal MCM Margolin; central ignition CZ 75 Kadet; .38 special ZKR551; 7.62 mmTT; 5.6 mm rapid-fire Walther, Bersa A 23; Glock 19; Hammerli standard 208. Ammunition comprised 5.6 mm (extra 75, R50); 9 mm Parabellum regular, 9 mm Parabellum, Combat 9 mm Parabellum (Parabelum Lapua).

The acquisitions of acoustic signals were carried out by the 2230 Bruel & Kjaer (Denmark) sound level meter with adapters preventing false steering of signals exceeding 140 dB. The device was connected to a 16-bit A/C transformer working at the speed of 44 100 samples per second. The details of our investigation have been described previously [11].

We analyzed the recorded material with use of the orthogonal adaptive parametrization by Shur. It enables a detailed description of several features of acoustic signals: the duration, the time/frequency structure and changes of the impulses' transient power. An extensive description of the method has been published elsewhere [31-33]. Here we summarize the idea of parametrization of acoustic signals.

$W_e(\omega) = 1 = W_y(\omega)\ |A(j\omega)|^2$

$A(j\omega)$ – a transfer function of the innovation filter

$y(t) \longrightarrow$ $\boxed{\text{the innovation filter } A(j\omega)}$ $\longrightarrow$ $e(t)$ = white noise

stationary signal $\downarrow$ → non-stationary signal

Shur coefficients $\{\rho_i\}$ → $\{\rho_i(t)\}$ the time structure

the Levinson algorithm $A(j\omega)$ → $A(j\omega,t)$

Parametric estimator
of the power spectrum
$W_y(\omega) = |A(j\omega)|^{-2}$ → $W_y(\omega,t) = |A(j\omega,t)|^{-2}$
the time/frequency structure

Power $P(t) = \Sigma_i|\rho_i|^2$ → $P(t) = \Sigma_i|\rho_i(t)|^2$ the transient power

An input acoustic signal is transformed by the perfect innovation filter with a transfer function $A(j\omega)$ into the innovation signal ($e(t)$), called 'white noise'. Shur coefficients are parameters of the filter and they are derived from the second level statistics of the input signal (power spectrum for f and covariance for t). Shur parametrization is a process of decorrealation of the input signal which enables calculation of the Shur coefficients and evaluation of the time-domain structure. With known Shur coefficients one can find the transfer function $A(j\omega)$ of the innovation filter (with use of the Levinson algorithm). Thus $1 = W_y(\omega,t)\ |A(j\omega,t)|^2$ and $W_y(\omega,t) = |A(j\omega,t)|^{-2}$.

The new objective measures of acoustic impulse signals have been proposed: the effective time of time-domain structure modification, the effective time of power density modification and the effective time of maximum level acoustic power.

The investigation of recorded real signals has been performed with prepared algorithms. They were used for description of: the duration, the time/frequency structure and changes in the power spectral density of signals.

Results

Our data show that a specific signal reaching sensors is combined of random signals emitted by the weapon (Fig. 1).

The situation is similar during individual and group trainings. An effective duration of a single impulse is between 250 and 800 ms and consecutive signals appear in 100-150 ms intervals [11]. Hypothetically two acoustic impulses could be concomitant. In our material (records from trainings and competitions) there were no such situations. Fig. 2 depicts the time-domain structure of a signal emitted by the Margolin sport pistol during an individual training (duration: 250 ms).

Figure 3 shows changes of the time-domain structure (Shur coefficients) in the selected six cells of the parametrization filter.

The time-domain structure (Shur coefficients) of a combined signal is modified within the first 0.5 ms. Further changes take place in the period between 3 and 5 ms, but they are relatively mild. After 5 ms changes of the time-domain structure are weak and account for approximately a few percent of Shur coefficients'variability. Generally, the time-domain structure of a signal reaching shooters' ears is modified within the first 3-5 ms for all kinds of weapon and ammunition.

Upon our data we assume that only direct signals and signals reflected from obstacles located no further than 0.5-0.8 m from a shooting stand are of importance to the hearing organ. A signal can be regarded as a single entity if the following impulse appears after at least 5 ms. An example of such a signal, recorded during a group training, is presented in Fig. 1.

Another important parameter for evaluation of noise exposure is the time/frequency structure of signals. A typical example of fluctuations of the spectral density of power is presented for the Margolin pistol (Fig. 4).

In case of the Margolin pistol the signal is broadband in the first phase, but after 0.5 ms several components disappear. Within this period (0.5 ms) the spectrum power decreases by 50 dB when compared with baseline. The results are comparable for other disciplines and weapons (data not presented). In the period between 3-5 ms it is noted a decrease of the spectrum power even by 90 dB. It is characteristic that low and medium frequency components (up to 6 kHz) are the most important for these impulses.

Another parameter that should be taken into account while evaluating the exposure to the impulse noise is the course of the transient power. Analyzing the distribution of the transient power associated with the Margolin pistol we have found that the highest level of the acoustic power lasts until the end of the first 1 ms (Fig. 5).

In the following 2 ms there is a decrease of power by 50 dB and in 3 ms there is a decrease of power by 70 dB. By 5 ms the power level is by 80 dB lower than the initial value (138.2 dBC). In other disciplines results are similar to the above (data not presented). The highest level of the acoustic power is observed between 1-2 ms and a decrease of power by 80-90 dB appears within the first 5 ms. Thus we conclude that an effective duration of the high level of the acoustic power is between 1 and 2 ms.

In our measurements the mean duration of a single acoustic signal was between 250-800 ms. The C-weighted sound peak pressure level was 138.2-165.2 dB (depending on the type of weapon and ammunition). The time structure

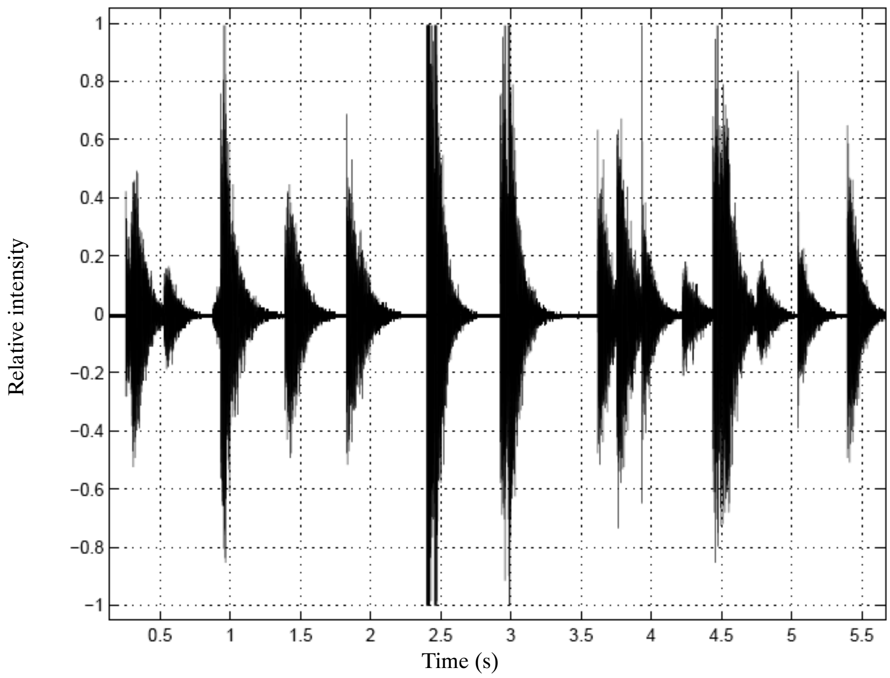

Fig. 1. Acoustic signals acquired during competition (relative intensity = maximal sound pressure/temporary sound pressure). Notes. Competition; 25-m shooting range; 32 competitors

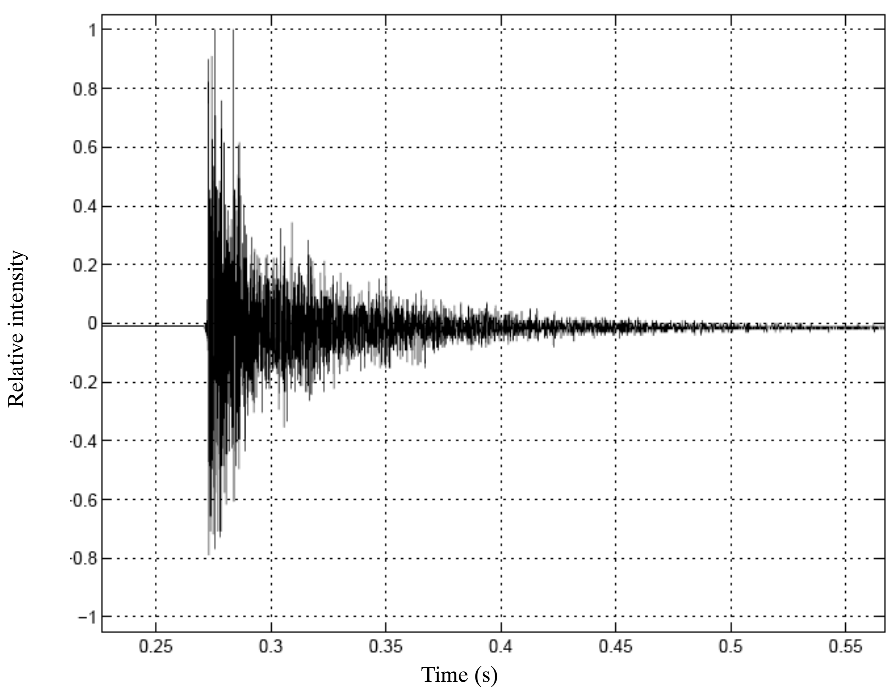

Fig. 2. Time history of an acoustic signal (relative intensity = maximal sound pressure/temporary sound pressure). Notes. Weapon: Margolin (Izhevsky Mekhanichesky Zavod, USSR); 25-m shooting range

of signals was modified in 3-5 ms. The changes in power spectral density took place between the 3rd and the 5th ms and changes in the transient acoustic power were between the 1st and 2nd ms.

Discussion

An acoustic signal reaching sensors in a given place of the acoustic field is a combination of random acoustic impulses emitted by N sources (N – number of shooters). The effective duration time of a resultant impulse is between 250-800 ms. Consecutive impulses appear in intervals of several or several hundred milliseconds. An objective analysis of the acoustic environment requires calculation of the probabilistic characteristics of signals in given points of the acoustic field. The weapon-derived impulse signals are nonstationary (their spectrum is time-varying) and their probabilistic characteristics change at random time points.

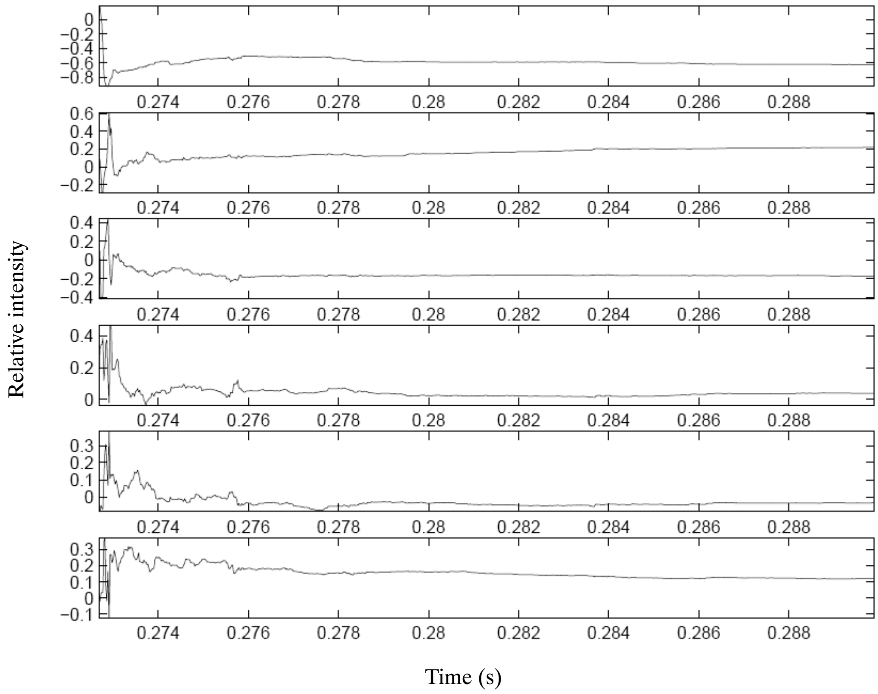

Fig. 3. Changes of the time-domain structure (Shur coefficients) in the selected six cells of the parametrization filter (relative intensity = maximal sound pressure/temporary sound pressure).
Notes. Weapon: Margolin (Izhevsky Mekhanichesky Zavod, USSR); 25-m shooting range

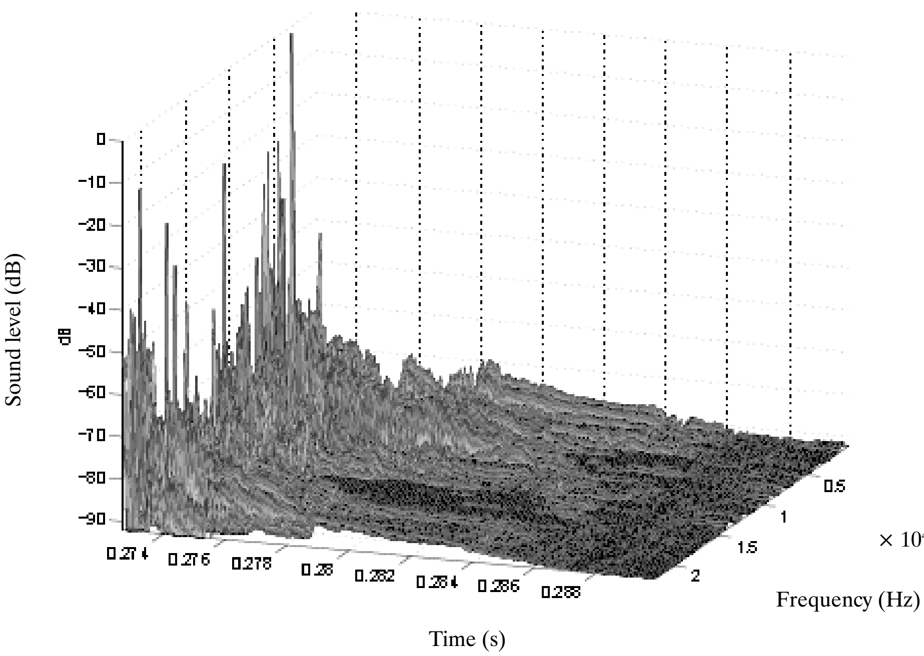

Fig. 4. Changes in power spectral density.
Notes. In this graph 0 dB = 138.2 dB of sound pressure; weapon: Margolin (Izhevsky Mekhanichesky Zavod, USSR); 25-m shooting range

For the above reasons it is difficult to analyze and interpret the acoustic phenomena in shooting sports.

A short-term spectral analysis, as a method to describe the time-domain structure of the nonstationary signals, is complicated. In view of our results, the most important parameters that should be analyzed are probabilistic characteristics of the nonstationary signals. Among the latter one can count: changes of the time/frequency domain of the power spectral density and changes of the transient power of a signal that correspond with the acoustic pressure in a given time point.

An effective method to calculate probabilistic characteristics of the nonstationary, random signals is the orthogonal adaptive parametrization by Shur. It enables

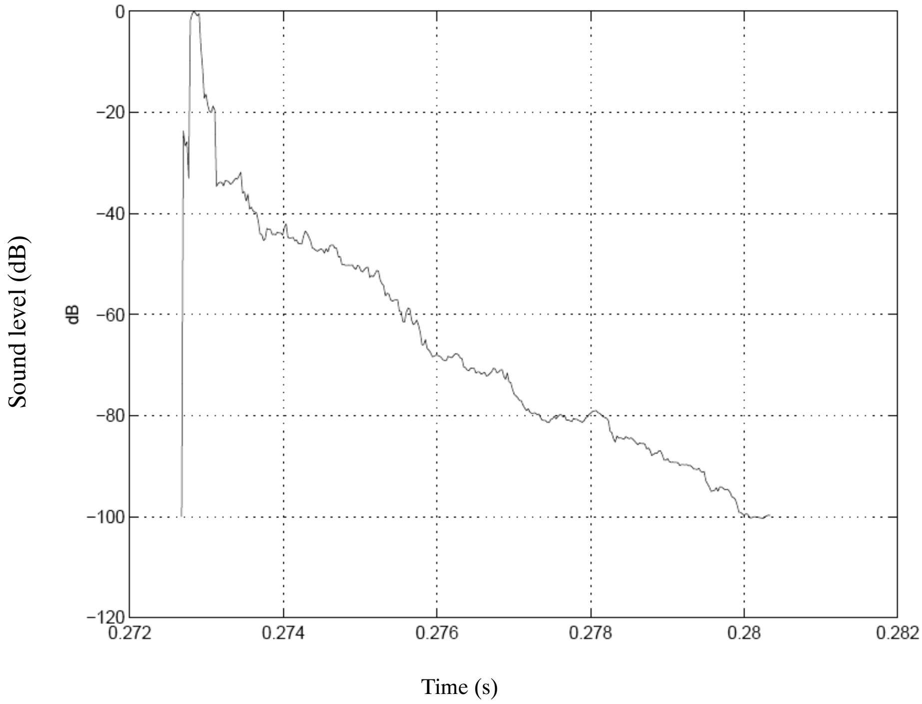

Fig. 5. Changes in transient acoustic power.
Notes. In this graph 0 dB = 138, 2 dB of sound pressure; weapon: Margolin (Izhevsky Mekhanichesky Zavod, USSR); 25-m shooting range.

a precise description of the acoustic signals' time-domain structure through parameters such as: fluctuations of components, changes of the amplitude and the frequency and the power. Upon our analysis of the acoustic environment of a shooting range we propose a set of new, objective parameters for the impulse noise screening: the effective duration of the time structure modification, the changes of the power spectral density and changes of the transient power.

Up till now, an assessment of the impulse noise was based on parameters such as: intensity, long-term analysis of the spectrum, number and time distribution of impulses. It did not comprise parameters important for the defense response of the hearing organ. Acoustic trauma and a mechanical damage of the middle ear have been observed when the acoustic pressure exceeded 170 dB. However levels of 125 dB can be harmful to the inner ear [25]. The upper allowed limit of the acoustic pressure for the occupational exposure is 135 dB. The European directive prohibits the exposure to peak pressure higher than 137 dB(C) with the hearing protection [34]. In shooting sports this limit is often exceeded.

The problem is that hearing loss is found in shooters using HPDs [17, 19, 35, 36]. It implies an important role of the frequency of repetition (number of impulses per second) and the time distribution of impulses [20]. Apart from the previously mentioned methods (peak level and energy evaluation) [22], it has been also introduced a theoretically based, mathematical model of the ear in which one can predict the risk of the hearing loss (AHAAH). This project was specially meant for the U.S. armed forces [27]. What seems intriguing there is a considerable interpersonal variability in regard to sensitivity to the impulse noise [37-40].

One of the methods used for the impulse noise screening is the long-term Fourier analysis. Although it analyses the spectrum of the impulse phenomenon (what is important for the ear physiology), it does not consider the time/frequency domain changes of the power spectral density and changes of the time-domain structure of a signal from different weapons and ammunition.

It has been shown that there is an association between the site of the ear damage and the maximal level of the acoustic pressure [41]. There have been proposed critical thresholds for a more detailed evaluation of the impulse noise exposure. The impact of noise exceeding these limits tends to become mechanical rather than metabolic [21, 26]. Sensitivity of the ear to permanent signals of high frequency has been proven, but data on the impulse noise is lacking. Several authors proposed screening procedures with audiometry above 8 000 Hz up to 20 000 Hz [37, 42, 43]. In this range the occupational exposure to the impulse noise may lead to the hearing damage, though according to the Fourier method the power spectral density of these frequencies may be higher. In view of our results, measuring the effective duration time of the spectral evolution of the power density is more sensitive and accurate as an indicator of the time/frequency changes of the impulse signals.

Common methods formerly used for the noise screening have been also questioned for the inadequacy of the A-weighing characteristics, especially for the aerodynamic impulses in sport shooting [22, 44]. The method of energy equivalence without concurrent evaluation of impulses' spectrum has serious limitations either [22, 45]. An important parameter for the noise assessment is the time structure of a single impulse (raising time, duration, falling time) and the frequency of repetition [44, 46]. The hearing organ is also affected by the number of impulses of lower maximal acoustic pressure [27, 47].

Many authors underlined the importance of the time distribution of impulses in regard to eliciting defensive/ /adaptation mechanisms in the middle ear, physiological and pathological fatigue and a permanent hearing loss [20, 22, 25, 48].

Parametric, adaptive estimation of signals' spectral density of power facilitates qualitative analysis of the acoustic impulse signals. Our approach is a new method to assess noise exposure in sport shooters, referees and coaches. It overcomes some previous limitations of signal noise evaluation as eg. of the AHAAH model that describes the hearing hazard of 95th percentile ear, what is not acceptable for small arms fire. Further research is needed for comprehensive auditory damage risk assessment of impulses with pressure between 115 and 160 dB [10].

None of the present methods to rate the impulse noise is accurate for sport shooting. The orthogonal, adaptive parametrization by Shur makes it possible to analyse the time structure, changes of the power spectral density and changes in the transient power of impulse signals. It provides spectral information in the time domain. These parameters together with the sound peak level objectively describe the impulse signal and they can be used to assess the effectiveness of the defense mechanisms of the middle ear [11]. The prediction of the auditory damage in our paper is based on signal measurements at the tragus of the shooter's ear (without HPD). In our previous study [12, 13] we found that only 68% of female sport shooters and 52% of male sport shooters used individual HPDs during training. Health problems (tinnitus, recurrent otitis media, transient hearing threshold shift or chronic hearing loss) were reported by respectively 77% and 55% of the investigated women and men. The most common reason not to wear a HPD was: deconcentration or health aspects (ear infections, allergies, overheating).

We have not evaluated the described method with HPDs yet. However we believe that the new interpretation of physical parameters of acoustic signals (the sound pressure and the time-domain and the frequency-domain) and a prediction of an immediate temporary threshold shift allow an optimal choice of HPDs.

The middle ear muscle plays an important role in increasing the acoustic impedance of the ear, changing its conductivity between 25-30 dB (depending on frequency). The reaction of the middle-ear muscle plays an important role in the prevention of the hearing damage. The reaction time of the muscle comprises: the latency, the duration of the maximal contraction and the relaxation time. Those features are related to the types of impulses and the duration of stimulation. Their behavior adds a non-linearity that changes with time and differentially as a function of frequency [6]. In view of our results, we suppose that the low and the middle frequency components significantly affect the ear and lead to pathological changes in the hearing organ. The method we use describes the structure of the impulse signal in the time and the frequency-domain. It makes possible to simulate an exposure of the ear in relation to a hypothetical jerk reaction [11].

In our data the duration of impulse acoustic signals in sport shooting was 250-800 ms and the C-weighted sound peak pressure level was 138.2-165.2 dB (depending on the type of weapon and ammunition). After analyzing the duration and the time/frequency structure of signals in shooting sports we assume that the time structure of a specific signal can be modified between the 3rd and 5th ms. Impulses that appear in intervals longer than 3-5 ms can be treated as separate ones. An acoustic signal impacts the ear in the first 3-5 ms, though its total duration is much longer. Apart from the time structure, the signal can be also characterized by the effective duration, changes in the power spectral density and the transient acoustic power. We observed that an initial wide spectrum characteristic of a signal narrowed after 1-2 ms. After the 1st ms the level of acoustic power decreased by 30-70 dB (depending on the type of weapon). Thus the highest effective level of acoustic power is expected between the 1st and the 2nd ms depending on the shooting event. Another important parameter in evaluating exposure to noise is the time/frequency structure of an impulse (changes in the power spectral density). At first the signal is broadband, but after 0.5 ms several components disappear and at this time the spectrum decreases by 50 dB. These results give an insight into the damaging action of the impulse noise in the aspect of the temporary and permanent threshold shifts.

Conclusions

Prevention of hearing loss requires regular otoacoustic exams, the conventional bandwidth tonal audiometry and an application of appropriate HPDs.

The exposure to the impulse signals in shooting sports cannot be properly evaluated by standard methods. Among specific features of the weapon noise that have not been considered by typical methods of noise screening are: the effective duration of signals, the time-domain structure modification, changes of the power spectral density and changes of the transient power.

Generally, the time-domain structure of a signal reaching the shooter's ears is modified within the first 3-5 ms for all kinds of weapon and ammunition. The adaptive parametrization by Shur enables a better recognition of the time and the time/frequency structure of acoustic signals in shooting sports. This novel approach covers the mechano-acoustic system of the middle ear. We believe that our method may give a new insight into the physiology of muscle fatigue under an exposure to the impulse noise (the tensor tympani and the stapedius muscle). It should explain the ear damage in sports shooters and broaden present models of hearing hazard assessment. Although the value of the Shur parametrization method in the evaluation of the impulse noise remains to be confirmed it will be likely used by designers of HPDs.

Piśmiennictwo
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