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EVALUATION OF OCCUPATIONAL EXPOSURE TO NOISE FROM THE HEARING CONSERVATION POINT OF VIEW

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Abstract. The paper presents the classification of noise according to its parameters (among others to the frequency range) to be considered as responsible for the potential hearing damage. Polish and international standards for various types of noise assessment at work places (including impulse noise) are discussed.

Basic instruments for noise measurements are described. Finally, attention is paid to various methods used for the reduction of exposure to noise and to protect the hearing of workers.

INTRODUCTION

Any action aimed at drawing up a coherent programme for hearing conservation in industry workers should be preceded by a survey to find out whether a hazardous noise condition does really exist. A general understanding of noise measurement methods and knowledge of fundamental descriptors of noise as well as of its properties contributing to hearing loss are essential for proper interpretation of measurement results and valid inferences in assessing exposure and taking appropriate measures to reduce the risk.

Noise is considered to be any unwanted sound that may produce and adverse effect on health and well-being of individuals of hearing populations.

From the physical point of view, noise means a sound of any acoustic nature resulting from a periodic vibration – compression of wave source in the air. Physical sound evokes physiological responses in the ear and auditory pathways. However, not all sound waves induce physiological responses, and they always depend on the frequency.

Human hearing is sensitive to the range of about 16 – 20 000 Hz (the audio-frequency range). The terms infrasound (0.1 – 16 Hz) and ultrasound (frequency greater than 20 kHz) have been introduced in order to distinguish the frequency range of an audible sound from the ranges where no auditory sensations are perceived.

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Polish standards of occupational hygiene introduce classification of noise in relation to its frequency range (10, 11, 12).

Thus, unpleasant and unwanted infrasound (2–16 Hz) and low frequency audible noise (under 50 Hz) is called "infrasonic noise", and high frequency, audible noise (above 10 kHz) and ultrasound of the frequency range 20–100 kHz is named "ultrasonic noise". Noise with the frequency spectrum in the 50–8000 Hz band is recognized as audible noise.

AUDIBLE NOISE

Normal hearing sensitivity is regarded as the ability to detect sound in the audio-frequency range. However, individual hearing sensitivity varies. Some of these variations may be attributed to the effects of different environmental factors. As a rule, hearing sensitivity declines with age, a condition known as presbyacusis.

Exposure to noise, mainly at work place, affects hearing sensitivity. While examining data on hearing loss caused by noise-exposure, aging process should also be taken into account.

In order to discuss the effect of noise on hearing, it is also necessary to distinguish hearing level, noise-induced threshold shift (NITS), hearing impairment and hearing handicap.

The hearing level applies to the audiometric threshold level of an individual or a group in relation to an accepted audiometric standard and it is sometimes termed "hearing loss".

The noise-induced threshold shift is the magnitude of hearing loss attributable to noise only after subtraction of presbyacusis values (including socioacusis).

The hearing impairment is generally referred to as a deviation or a negative change in the hearing threshold. It is usually understood as a change in the structure of function; for example in the International Standard ISO 1999 only impairment of function is considered (4).

The low fence for hearing impairment has been defined in Poland as a pure tone average of, at least, 30 dB at audiometric frequencies 1, 2, 4 kHz in the better ear (after age correction) (15).

The hearing handicap (or disability) is defined as a hearing impairment severe enough to affect one's personal efficiency in activities of daily living, manifested usually in terms of understanding of conversational speech in low levels of backround noise.

Hearing impairment caused by noise exposure depends upon the noise level, constituent frequencies, duration and exposure distribution during a typical work-day, and the total length of occupational exposure.

Audible noise is usually classified according to:

1. Frequency spectrum:
   a) continuous spectrum,
   b) spectrum with audible discrete tones;
2. Variability in time:
   a) steady noise (a noise with negligible small fluctuations within the period of observation – ± 5 dB),

b) non-steady noise (noise level shifts significantly during the period of observation),
   * fluctuating noise (noise level varies continuously to appreaciable extent during the period of observation),
   * intermittent noise (noise level suddenly goes down to the ambient level several times during the period of observation, the time during which the level remains at a constant value different from that of ambient being of order of magnitude of 1 second more),

c) impulse noise (a noise consisting of one or more bursts of sound energy, each lasting less than 1 second),
   * quasi-steady impulse noise (a series of noise bursts of comparable amplitude with intervals shorter than 0.2 s between individual bursts),
   * an isolated burst of sound energy.

As the human sound perception processes are complex, for simplicity of noise measurements many frequency weighting networks (A, B, C, D, E, SI) have been introduced and internationally standardized. For example A, B and C filters are intended to match the ear-response curves at low, moderate and high levels loudness, respectively (so A, B and C filters follow more or less the 40, 70 and 100 phones contours, respectively). The D-weighting approximately follows a contour of perceived noisiness, and is used for a single event aircraft noise measurement. The SI -weighting suggested by Webster for the assessment of speech interference, concentrates heavily on the predominant speech frequencies (5).

The A-weighting is by far more widely used among those scales to determine exposure to noise at work places for hearing conservation purposes.

In Poland according to standard and other recommendations an equivalent continuous A-weighted sound pressure level ($L_{Aeq,\ T}$) is used to estimate the exposure to steady, non-steady and impulsive quasi-stationary noise (Table 1) and 3-dB equal energy rule is incorporated (11, 14, 20). The permissible sound pressure level for hearing conservartion purposes is established at 85 dB(A)[1].

$L_{Aeq,T}$ is the A-weighted energy mean of the noise level averaged over the measurement period. It can be considered as the continuous steady noise level which would have the same total A-weighted acoustic energy as the real fluctuating noise measured over the same period of time (T).

The equal energy rule is the theory in which the hearing hazard is determined by the total sound energy entering the ear each day. This rule has a natural value, since the exposure dose is quite simple to assess and, according to epidemiological data, it is reasonably well correlated with the accumulated physical damage. The rule allows a 3-dB increase in steady sound level for each halving of the duration.

In the case of impulsive or impact noise, whose frequency of repetition is less than 1 Hz, it is recommended to measure peak (un-weighted) sound pressure level and to determine the total number of impulses or impacts per working day.

When the daily exposure is composed of two or more periods of various types of noise (steady, non-steady, quasi-stationary impulsive noise and isolating impulse noise), their combined effects are recommended to be considered as the sum of the following fractions (1):

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[1]Admissible $L_{Aeq,T}$ ensuring proper conditions for performing basic function at chosen types of work places is also settled.

Table 1. Admissible values of sound pressure level at work places and recommendations for audible noise measurements

Types of noise		Measured parameters	Permissible levels[1]
ISO 1999	* steady * non-steady * impulsive	* A-weighted sound exposure $E_{A,T}$ or * daily A-weighted exposure $E_{A,D}$ or * equivalent continuous A-weighted sound pressure level $L_{Aeq,T}$ or * noise exposure level normalized to a nominal working day $L_{EX,8h}$	none
Up-to date Polish Standard PN-84/N-01307 and other recommendations	* steady * non-steady * impulsive-quasi-stationary[2]	* equivalent continuous A-weighted sound pressure level $L_{Aeq,T}$	85 dB (A) – 8h
	* impulsive or impact noise	* peak un-weighted sound pressure level $L_{LIN,\ PEAK}$ and * number of impulses N	130 dB – 100 120 db – 1000 110 dB – 10000
Project of Polish Standard	* steady * non-steady * impulsive	* A-weighted sound exposure $E_{A,T}$ or * noise exposure level $L_{EX,8h}$ and * maximum of $L_{A,S}$ or $L_{Aeq,1s}$ and * peak C-weighted sound pressure level $L_{C,PEAK}$	$3.64 \times 10^5 Pa^2s$ 85 dB(A) – 8h 115 dB(A) 135 dB(C)

1 – for hearing protection

2 – 10 dB should be added to the measurement results

$$\sum \frac{t^i}{T_i} \neq \sum \frac{n_i}{N_i} \qquad (1)$$

where:

t_i – total duration of exposure to noise at level $L_{Aeq,ti}$
T_i – total duration of exposure permitted at level $L_{Aeq,ti}$
n_i – total number of impulses or impact noises at level $L_{LIN,peak,i}$
N_i – permitted number of impulses or imapct noises at level $L_{LIN,\ peak,i}$.
The sum should not exceed 1 (20).

According to international standards $L_{Aeq,T}$ (especially noise exposure level normalized to a nominal 8 h working day ($L_{EX,\ 8h}$) or daily A-weighted sound exposure ($E_{A,D}$) are used in order to describe all types of impulsive noise and steady or non-steady noise (6).

Apart from that, there is a proposal of the International Standard ISO how impulsive noise should be measured, among other cases, in the occupational environment (8).

Nevertheless, various experimental data and epidemiological studies suggest that impulse noise and partly impulsive noise are more harmful than quasi-steady noise of the same energy (15, 18).

The proposal of new Polish criteria for evaluation of noise at workplace considers new requirements and recommendations established in the EEC (86/188/EEC) and ISO documents as well as recent advances in science (1, 2, 13, 17, 19).

The International Standard ISO 1999 (1990) specifies a method for calculating the expected noise-induced permanent threshold shift (NIPTS) in the hearing threshold levels of adult population due to various levels and durations of occupational noise exposure. For the assessment of hearing impairment due to exposure to noise, it presents formula to calculate the NIPTS for audiometric frequencies from 0.5 to 6 kHz, for 8 hours per day, daily A-weighted sound exposure of 364 Pa^2s to 1.15×10^5 Pa^2s (equivalent continuons A-weighted sound pressure level for a standard 8 h working day from 75 dB to 100 dB), and duration of exposure lasting from 0 to 40 years. Based on this standard, adopted by several countries, occupational exposure limits are specified in the range of $L_{Aeq,8h} = 85 \pm 5$ dB (A), with an increasing tendency towards reaching lower limits. 75 dB(A) can probably be considered as a limit below which there is little or no risk of permanent hearing damage and protective measures are not necessary. Hearing conservation programs should be adopted in the case of routine occupational exposure to higher levels (4).

INFRASOUND

It has been usually assumed that infrasound is inaudible. However, it is not true any more. Infrasound can be heard by the human ear, and when it becomes loud, it can be annoying. The annoyance associated with exposure to audible infrasound has been the subject of a number of laboratory experiments. For example, contours of equal annoyance were determined for pure tones in the frequency range from 4 to 31.5 Hz. The curves show a narrowing of the dynamic range of the ear at low frequencies. The same pattern is seen for equal loudness curves, so the annoyance of infrasound is closely related to the loudness sensation (9).

Moreover, infrasound affects the human being, especially the hormonal and the central nervous systems. The high acoustic pressure levels of infrasound can damage semicircular canals (the organ of balance), the hearing organ and can excite resonant oscillations of the frequency range 0.1 – 25 Hz in particular parts and organs of the human body (3).

The Polish Standard gives the admissible values of acoustic pressure levels of infrasonic noise only at work places (Table 2) (12). It also presents measurement techniques and specifies the equipment used.

Table 2. Infrasonic noise, admissible values of acoustic pressure level at work places (time exposure- 8 hours) specified in the Polish Standard PN-86/N-01338

	Octave bands with middle frequencies (Hz)			
Admissible acoustic pressure levels [dB]	4	8	16	31.5
* for health protection at all work places;	110	110	110	105
* ensuring proper conditions for performing basic functions in observational dispatcher cabins, remote control in premises for precise works;	90	90	90	85
* in premises for administration, theoretical works, data handling and in design offices.	85	85	85	80

Whereas in the International Standard (ISO/DIS 7196.2) it is recommended to use G frequency-weighting network in order to describe infrasound (1 – 20 Hz). There is no information about permissible levels.

ULTRASOUND

Exposure of a human being to low frequency ultrasound (16 – 100 kHz) can be divided into two distinct categories; one is via direct contact with vibration solid or through a liquid coupling medium, and the other is through airborne conduction.

In the case of airborne ultrasound exposure, the ear is, at least, one of the critical organs. Exposure to ultrasound can cause hearing damage.

The Polish Standard recommends to measure acoustic pressure levels in 1/3 octave bands in the frequency range 10 – 100 kHz in order to describe ultrasonic noise at work places (Table 3) (11).

Table 3. Ultrasonic noise permissible values of acoustic pressure levels at work places (time exposure – 8 hours) specified in the Polish Standard PN-86/N-01323

1/3 octave bands with middle frequencies (kHz)	Permissible acoustic pressure level (dB)
10, 12.5, 16	80
20	90
25	105
31.5, 40, 50, 63, 80, 100	110

This Standard also gives permissible acoustic pressure levels, and describes measurement techniques and appropriate instruments. Meanwhile the International Standard (IEC TC 29/WG 16) suggests U-weighting network for measuring airborne ultrasound.

MEASUREMENT INSTRUMENTS

The portable sound level meter is possibly the most convenient way of bringing together all elements necessary for a sound measurement system.

Recent rapid developments in electronics, especially in the integrated circuits and digital techniques have enabled designers to build in ever more functions and facilities into a new generation of instruments which at the same time reduce weight and bulk and increase the user's comfort. A typical example of a new generation of instruments are sonometers designed for assessing cyclic, fluctuating and impulsive noise as well as hearing damage risk. They include A, C, LIN and ALL PASS frequency weighting and RMS "Fast", "Slow", and "Impulse" time constants as well as "PEAK" response with a 50 μs rise time. The following measuring modes: $L_{Aeq,T}$, Sound Exposure Level (SEL), current RMS and PEAK sound pressure level, maximum and minimum RMS SPL, and maximum PEAK SPL during the measurement period are simultaneously up-dated and can be displayed at any time using a display selector (Table 4).

Filter sets can be attached directly to them for carrying out octave or 1/3 octave analysis of noise in the field. Some of them can, in addition, be fitted with Infrasound and Ultrasound Filter Set in order to measure infra- or ultrasonic noise according to international standards.

Table 4. Examples of portable instruments for noise measurements (chosen specification)

Type of meter		Sound level meter				Sound & Vibration Analyzer
		B & K 2230	B & K 2231	B & K 2236	SONOPAN IM−10	SVAN 912
Type of noise	steady	yes	yes	yes	yes	yes
	non-steady	yes	yes	yes	yes	yes
	impulsive	yes	yes	yes	yes	yes
Frequency responses	linear	yes	yes	yes	yes	yes
	weighted	A, C	A, C	A, C	A,C	A, C
	filters	B & K 1624/25	B & K 1624/25/27	yes[1]	SONOPAN OF−10	yes[7]
Measurement modes	RMS[2]	F, S, I	F, S, I	F, S, I[4]	S	S, F, I
	PEAK	yes	yes	yes[3,4]	yes[5]	yes
	Max Hold	yes	yes	yes[4]	yes	yes
	Min Hold	yes	yes	yes[4]	no	yes
Averaging		$L_{eq,T}$, SEL	$L_{eq,T}$, SEL	$L_{eq,T}$,[4] SEL	$L_{eq,T}$,[6] SEL	$L_{eq,T}$ SEL
Dynamic range	[dB]	70	70	80	60	80
Complies with standards	IEC 804	1	1	1	1	1
	IEC 651	1(Impuls)	1(Impuls)	1(Impuls)	1	1
	ANSI S1, 4,	S1	S1	S1		

B & K (Bruel & Kjaer – Denmark); SONOPAN – SONOPAN Ltd. Poland; SVAN – SVANTEK Ltd. (Poland); 1624 – octave filter set (31.5 Hz−16 kHz); 1625 – 1/3 – 1/1 octave- filter set (20 Hz−20 kHz); 1627 – infrasound and ultrasound filter set; OF−10 – octave filter set (31.5 Hz – 8 kHz);

1 – octave band-pass filters (31.5 Hz – 8 kHz) available only with type 2236 C and 2236D

2 – RMS time constant; FAST, F; SLOW, S; IMPULS, I

3 – simultaneous $L_{eq,T}$ and PEAK measurement with independent frequency weighting

4 – logged results $L_{eq,T}$, maximum RMS SPL , and maximum PEAK SPL

5 – overflow 135 dB(C) PEAK checking and signalling

6 – maximum $L_{eq,1s}$ holding

7 – FFT analysis up to 25.6 kHz (6.4 kHz Real Time Band) 1/1 and 1/3-octave digital filters and infrasound filter set (G-weighting)

The need to ensure occupational hearing conservation among the noise exposed employees during their normal working day, has led to the development of a new type of specialized integrating sound level meter (dosimeter) which determines directly the "noise dose". The noise dose is a measure of the total A-weighted sound energy received by an employee. It therefore depends not only on the level of the noise but also on the length of exposure to noise. Often, both the noise in each work place and the length of time spent there vary widely, so an instrument which can be worn by the employee himself is often preferable to the alternative method of measuring the noise in each place of work, (deciding how much time is spent there), and summing up individual exposures to be representative of the entire working day.

For example a noise dose meter type 4436 (B & K) calculates, among other parameters:

* the sound exposure.
* the daily personal noise exposure level ($L_{EP,d}$),
* the sound pressure level and L_{eq} every second.

From these calculations the dosimeter works out the distribution and cumulative distribution of recorded noise levels, and also produces a time history of measurement results. It also can be used as an integrating sound level meter (type 2).

Although measurements of $L_{Aeq,T}$ require the use of an integrating averaging sound level meter, there are a number of techniques available for estimating $L_{Aeq,T}$ where an appropriate equipment is not accessible.

The A-weighting does not perfectly account for different frequency sensitivity in humans. Certain types of low and high frequency noise can be more annoying or potentially harmful than a simple A-weighting measurement might indicate. The C-weighting includes a much wider range of audio-frequency than A-weighting. The numerical difference between simultaneous measurements using both the A-and C-weighting indicates the amount of more extreme frequencies.

A complete description of various frequencies present in the sound requires the use of frequency analyzer. There are two main types of frequency analyzers in common use (the Fast Fourier Transform (FFT) analyzer and real-time frequency analyzer with band-pass fractile octave filters).

The FFT analyzer is good for detecting narrow band, tonal and harmonic components in noise, but the frequency display does not provide as good direct correlation with subjective impressions as the second main type of frequency analyzers. This is because human frequency resolution tends to be logarithmically spaced across the frequency range; whereas the frequency resolution of the FFT analyzer is linearly spaced across the frequency range.

The other main type of frequency analyzer uses logarithmically spaced analysis of bandwidhts which should be located at internationally agreed octave and one-third octave spacing. Frequency resolutions down to 1/24 octave are currently available in commercial instruments. Frequency analysis using a fractional octave analyzer ususally gives a closer correlation with subjective impressions of the sound than by using the FFT analyzer, but sometimes it is less useful in view of the cost-effective noise control (4).

CONCLUSIONS

Exposure to noise, especially audible, at work place affects hearing sensitivity. The potential hearing damage of a given noise depends on its parameters and length of time.

The A-weighting $L_{Aeq,T}$ measurement is most widely used in assessing exposure to noise in the occupational environment. It allows to evaluate the expected noise-induced permanent threshold shift, but it cannot be used to predict or assess the hearing impairment or hearing handicap of individual persons.

The A-weighted sound pressure level provides an approximate guide to subjective loudness of sound, it does not, in any way, describe the overall character of information content. On the other hand, the equivalent continuous sound level, $L_{Aeq,T}$ gives only the average energy content over time and therefore cancels the pattern of variations over time which may be important in determining subjective responses.

When the measurements reveal that the sound pressure levels at work places are too high, steps must be taken to reduce them. To draw up a programme for reducing noise exposure it is not an easy task, however there are four general guidelines which, if followed, can help in finding the best possible solution. They are as follows:

1. to reduce the noise at its source; this may be done by acoustic treatment of machine surfaces, design changes or purchasing a new, more silent machine;

2. to block the sound transmission path; this may be done by placing an enclosure or acoustic screens around the machine and mounting it on vibration isolators to prevent transmission through the floor; noise is further reduced by coating walls, ceiling and floor with absorbing materials;

3. to equip the exposed persons with ear protectors and to introduce the monitoring audiometry;

4. to shut down the machinery; in emergency cases, this step must be considered; it is also possible to limit the operation hours, move the annoying noise source to another location, or rotate workers so their exposure is reduced.

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