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DETERMINING THE NOISE IMPACT ON HEARING USING PSYCHOACOUSTICAL NOISE DOSIMETER

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This research study presents the designed noise dosimeter based on psychoacoustical properties of the human hearing system and, at the same time, evaluation of time and frequency characteristics of noise. The designed noise dosimeter enables assessing temporary threshold shift (TTS) in critical bands in real time. In this way it is possible monitoring the hearing threshold shift continuously for people who stay in the harmful noise conditions. Moreover, the psychoacoustical noise dosimeter (PND) provides the functionality which determines time causing an increase of the assumed hearing threshold shift along with time required for recovery of a hearing threshold toward its initial value. Noise exposure levels, its duration along with hearing examination have been first measured in the acoustically controlled environment. Pure-tone audiometry has been used for hearing examination. This has been conducted in constant time intervals, during noise exposure as well as during resting time (time required for hearing recovery). The examination aims at measuring hearing threshold at 4 kHz. The important part of this study is validation of the dosimeter performance in the real noise exposure situation. In this case the whole noise measurement scenario encompasses both noise exposure effects, and hearing examination before and after noise exposure. The hearing examination has been extended by the distortion products otoacoustic emission method (DPOAE). The measurement results obtained in real conditions have been compared with those which were computed by means of the presented psychoacoustical noise dosimeter.

Keywords: urban noise, temporary threshold shift, hearing measurements, psychoacoustic noise dosimetry.

1. Introduction

At present the noise is regarded as one of the serious civilization threat [1]. The effect of the high noise levels evokes serious consequences for the hearing system. It may cause an irreparable destruction of the sensitive structures in the inner ear [2, 3].

Issues regarding to the occupational threats to the noise are widespreadly considered in the contemporary literature [4–7]. It is necessary to notice that the common access to audio equipment (such as portable mp3 players) and various types of entertainments could create a hide health hazard for their users [8–12]. In this paper the concept and practical implementation of the new type of noise dosimeter was presented. Its operation depends on the determination of the hearing effect induced by noise. Optimization and evaluation of the designed dosimeter in the real noise exposure conditions constitute a significant part of this paper.

2. Psychoacoustic noise dosimeter

Present methods of noise-induced hearing loss estimation are based mainly on equal energy hypothesis [7]. This approach focuses on the assessment of energy quantity which affects a hearing system. The time changes of noise is neglected, and the main emphasis is placed on the assessment of an equivalent sound level value. However, in many cases this approach could be insufficient. The analysis of numerous literature data, including testing of an exposure results to different types of noise, can provide a knowledge that time changes and noise spectrum plays an essential role in generating hearing loss [3, 13, 14]. Taking these data into consideration, a novel method of risk estimation of hearing impairment has been proposed by the authors, which is based on modeling influence of given noise type results. A modified Johnston's psychoacoustic model, which allows for the global distribution of a basilar membrane deflection within critical bands, was employed [15]. In Fig. 1 a scheme of the psychoacoustic noise dosimeter (PND) has been presented.

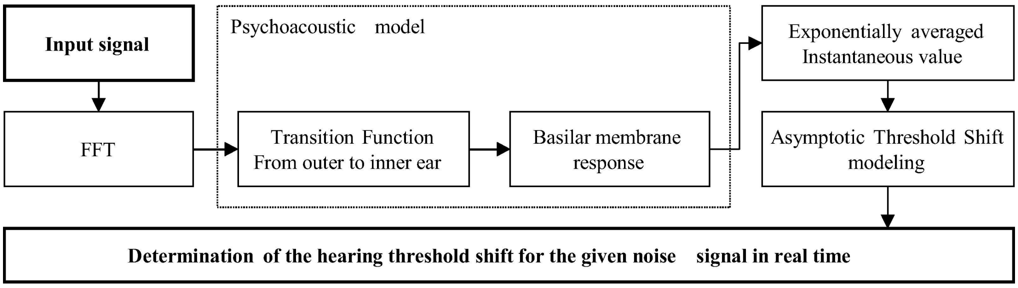

Fig. 1. The general scheme of the psychoacoustic noise dosimeter.

The model functioning is based on the analysis of a basilar membrane answer to noise in critical bands. First the power spectrum of noise is determined. Afterwards, it is corrected by taking into account transition from the outer to the inner ear. The function proposed by E. TERHARDT was used, which is given below [16]:

$$L_{TH}(f) = 3.64(f/1000)^{-0.8} - 6.5\exp(-0.6(f/1000 - 3.3)^2) + 10^{-3}(f/1000)^{-4}. \tag{1}$$

Subsequently, particular spectrum coefficients are grouped into critical bands, according to the bark scale. Then the noise level in particular critical bands is calculated. This assesses the extent to which the basilar membrane is stimulated. Its answer is determined by multiplication of the instate stimulation value levels by the characteristics of hearing filters for the particular critical bands. The characteristic of a hearing filter proposed by Terhardt has been applied, as shown in Eq. (2) [9]. It has a very essential property relying on changing the shape right slope of the filter according to the noise level. It enables a faithful modeling of the processes occurring in the inner ear.

$$S_{\mathrm{dB}}(i,l,E)=\begin{cases} 27(i-l), & i\le l,\\ (-27-230/f_c[l]+2\log_{10}E)(i-l), & i>l, \end{cases} \tag{2}$$

$S_{\mathrm{dB}}(i,l,E)$ – level on the out of the hearing filter, expressed in dB, i, l – indexes of the critical bands, E – noise level for i critical band, $f_c[l]$ – center frequency of the l critical band expressed in Hz.

Basilar membrane displacement value obtained in this way is exponentially averaged afterwards. This action reflects inertia of processes occurring in the inner ear. Averaged values are used for the assessment of hearing Asymptotic Threshold Shift (ATS). To calculate the ATS parameter Eq. (3), proposed by MILLS *et al.*, was used [17]. This parameter depends on the frequency and the level of noise. It determines the maximum threshold shift of the hearing sensitivity for a given noise level. The work done by CLARK, who used the laboratory animals exposed to a very high noise level, confirmed a correctness of such relation even for very high ATS values (up to 60 dB) [14]. This relation is crucial in the process of temporary threshold shift determination in real time on the basis of the actual noise level.

$$\mathrm{ATS}=1.7\left(10\log_{10}\left((L_e+L_c)/L_c\right)\right), \tag{3}$$

L_e – noise level for given critical band after hearing filter section, L_c – the critical level (the values of that parameter were presented in the Table 1.

Table 1. Critical levels for a particular critical band [17] employed in the psychophysiologic noise dosimeter.

Numbers of the critical bands	1–4	5–9	10–11	12–14	15–16	17	18	19	20	21–24
Frequency ranges in Hz	0 400	400 1080	1080 1480	1480 2320	2320 3150	3150 3700	3700 4400	4400 5300	5300 6400	6400 15500
Critical level L_c in dB SPL	88	84	82	78	76	75	74	72	68	70

Finally these values are subjected to exponential averaging, that reflects a process of hearing threshold shift. Therefore this model enables to assess TTS (Temporary Threshold Shift) in critical bands, time required to obtain a determined hearing threshold shift, and time for a recovery of a hearing threshold to its initial value. For calculation the recovery time the Eq. (4) was used [17]. An operation of the model enables to determine the hearing threshold shift for the given noise during exposure.

$$T_{\text{Recovery}} = -\tau \cdot \ln\left(\frac{\delta}{\text{TTS}_{\text{inst}}}\right), \tag{4}$$

τ – time constant for TTS restitution process, δ – value which means that the TTS effect is over, in the PND algorithm the 0.1 dB was used, TTS_{inst} – instantaneous value of the TTS used for T_{Recovery} calculations.

The additional advantage of the developed algorithm is the utilization of the psychoacoustic model in the noise dosimeter. The unique feature of the presented dosimeter is an assessment of the audible results evoked by the noise exposure in the real time. It gives the opportunity to know the temporary threshold shift characteristic for a given type of noise. Executing the PND algorithm is also necessary to obtain a detailed information on hearing threshold shift. A very important feature of the algorithm is the determination of time required for hearing recovery to its initial value after the noise exposure. In this way it is possible to know a detailed report on noise threat from a noise station mounted in places where noise is excessive. This means that special procedures available in the PND enable to find out which noise frequencies are the most dangerous for a human hearing system.

3. The methodology of noise and hearing measurement in the acoustically controlled environment

Students of age of 21–22 years participated in the hearing examinations after the noise exposure in an acoustically controlled environment. The main aim of this research was to determine time constants for the TTS effect produced by noise both for an exposure and for a recovery time. Before and during every measurement series the noise level in the exposure room was controlled using the Bruel & Kjaer sound level meter of type 2260. The noise level was set at 88 dB(A). Additionally, during each exposure, the noise level by the person's ear has been checked for 30 seconds. The band-pass white noise, limited to the range of 1–6 kHz was used as a stimulating signal. In Table 2 the L_{Aeq} values in one-third octave band of the stimulus signal are shown.

Table 2. L_{Aeq} values in one-third octave band of the stimulus signal.

F [Hz]	1000	1250	1600	2000	2500	3150	4000	5000	6300
L_{Aeq} [dB]	67.3	71.8	74.6	77.9	77.8	79.8	81.5	81.9	78.9

The hearing was examined for every person just before the noise exposure. Subjects were exposed to noise three times. The single exposure lasted 10 minutes. The hearing threshold was examined immediately after every exposure using the pure-tone audiometry for 4 kHz only with 1 dB step. After the exposure, the hearing was examined once again during resting time (time required for hearing recovery) every 8 minutes. The hearing examination for a single person took about 2 minutes.

4. Noise and hearing measurements in real situations

The noise measurements were done by means of the noise monitoring station, developed at the Multimedia Systems Department Gdańsk University of Technology. It constitutes a part of the Multimedia Noise Monitoring Systems [18, 19]. The measurement station has functionality as a typical sound analysis equipment. The measurements were performed in selected students' musical clubs. The data gathered were utilized to perform the noise dose analysis. This was done to determine the noise exposure in considered places. The hearing was examined twice, first just before the exposure to a given type of noise, and then immediately after the exposure. The performed analysis combined the obtained noise and hearing measurement results.

The following noise parameters $L_{\mathrm{AF\,min}}$, $L_{\mathrm{A\,eq}}$, $L_{\mathrm{AF\,max}}$ were measured independently over broadband and in one-third octave bands ($L_{\mathrm{AF\,min}}$, $L_{\mathrm{AF\,max}}$ – the lowest and highest A-weighted sound levels for fast time weighting, that occurred during the measurement, and $L_{\mathrm{A\,eq}}$ – the A-weighted equivalent continuous noise level over a specified period of time that represents the same energy as the actual time varying noise signal). A cumulative distribution for time history values of L_{AF} instantaneous levels was also calculated. The noise measurement have been performed according to the PN-N-01307 norm [20]. For all measuring series, a place where people gather most often was selected in order to determine correctly a real noise dose to which they are exposed.

Hearing examination employing the DPOAE method was performed using GSI 60 DPOAE system. The following parameters of the stimuli were used during tests: L_1 equals 65 dB SPL, L_2 equals 55 dB SPL, $f_2/f_1 = 1.2$, DP frequency (geometric mean): 1062, 1312, 1562, 1812, 2187, 2625, 3062, 3687, 4375, 5187, 6187, 7375 Hz. The DP signal level and noise background for every stimuli were registered. The test result was accepted if the difference between the evoked otoacoustic emission signal and the noise background was no less than 10 dB. For pure tone audiometry only selected frequencies were examined: 1000, 1500, 2000, 3000, 4000, 6000, 8000 Hz. The stimuli for each frequency were presented starting from the minimal loudness. The reason of such a selection of parameters was because the noise impact on hearing system is the strongest for middle and high frequencies. The test was carried out in special rooms adapted for this purpose.

5. The results obtained in the acoustically controlled environment

The examinations were carried out on 49 persons (98 ears) who are of age of 21–22 (students). The 290 single noise measurements have been performed (one measurement for every exposure). The average $L_{\mathrm{A\,eq}}$ level for measurements performed was equal to 88 dB(A) and the standard deviation was equal to 0.9 dB. The detailed analysis of obtained results was then performed. The normalization of the obtained characteristics of the TTS changes for particular ears was done. The references value for every characteristic was the corresponding maximum value of the TTS level. This operation allowed comparison and statistical analysis of the whole measurement series. In the Table 3 the whole hearing measurement results were shown.

Table 3. The collective results of the TTS changes produced by the noise exposure. All values are expressed in dB.

	TTS min	TTS avg	TTS max	Std Dev σ	Median	Simulation
Start	−11.8	**0.0**	10.2	5.9	**0.0**	**0.0**
Exposure 1	−4.8	**5.4**	10.2	3.5	**6.0**	**4.3**
Exposure 2	−7.8	**7.1**	10.2	3.2	**7.0**	**7.1**
Exposure 3	−12.8	**8.4**	10.2	4.0	**10.0**	**8.9**
Recovery 1	−11.8	**3.5**	10.2	3.9	**4.0**	**5.4**
Recovery 2	−11.8	**3.0**	17.2	5.1	**3.0**	**3.3**
Recovery 3	−6.8	**−0.2**	10.2	3.7	**0.0**	**2.0**
Recovery 4	−7.8	**−0.3**	3.2	3.7	**1.0**	**1.2**

On the basis of the obtained hearing measurement the time constant for the assumed exponential model of the TTS changes was calculated. It is equal to 30 minutes for the growing phase. It is important to emphasize that the recovery phase should be shorter, however in the first version of the PND algorithm a single time constant both for growing and recovery phase was used. The simulation results of this configuration are presented in Fig. 2 (the series labeled as “PND results 2”, dotted line).

The difference between simulation characteristic and real (average and median) measurement data is significant, especially for the recovery phase. For this reason the additional time constant for resting time was determined. It equals 20 minutes. In Fig. 2 the results obtained for the updated PND algorithm with two different time constants for growing and recovery phase were presented as a “PND results 1” series. The conformity between simulation and obtained hearing measurement results is clearly visible. Moreover, it is essential to notice that the model correctly reflects the decrease of the TTS level in breaks between consecutive noise exposure phases. For the evaluation of the PND operation the Pearson’s test was used. The calculation was done using real data and the corresponding simulation values. The Pearson’s test for pair Average – “PND results 1” equaled: 0.945, for pair Median – “PND results 1” equaled: 0.943. It means that the results of the TTS changes computed by the developed PND are consistent with the obtained hearing measurement.

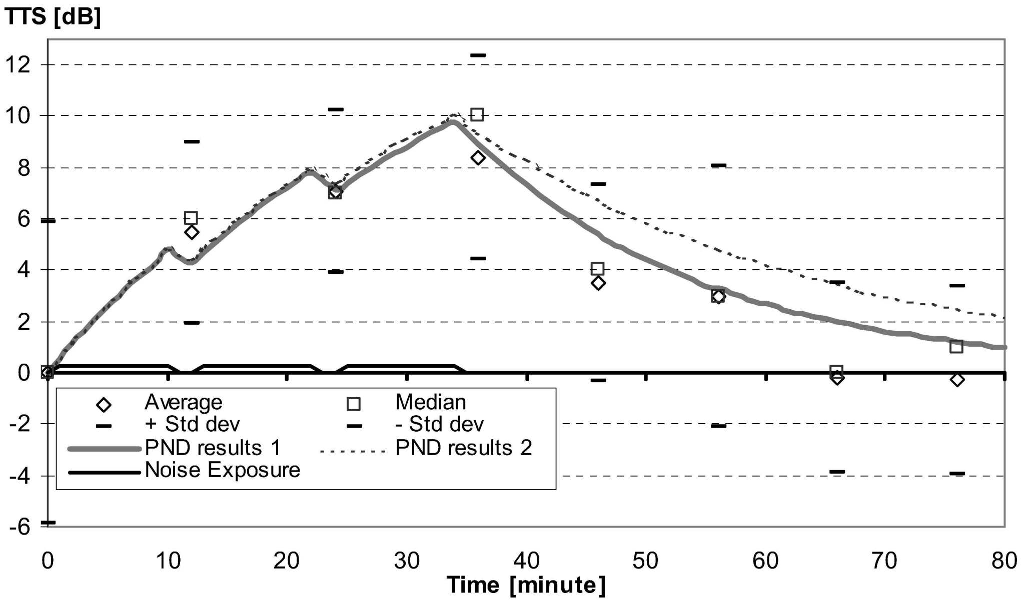

Fig. 2. Measured and simulated TTS changes produced by noise for 4 kHz. The grey and thin black dotted lines reflect the PND results.

6. The noise and hearing measurement results obtained in real noise exposure situations

6.1. Noise measurement results

In the Table 4 the noise measurement results obtained during four different exposures in the selected students' music clubs were presented. The noise measurement durations for Clubs 2–4 were similar and amounted to 90 minutes. In the first club the time exposure was the shortest one and amounted to 75 minutes. The obtained $L_{\mathrm{A\,eq}}$ values for Clubs 1, 2 and 4 are very similar.

Table 4. Noise measurement results obtained in the clubs considered. The noise levels were expressed in dB(A), time was expressed in minutes.

Type of exposure	$L_{\mathrm{AF\,min}}$	$L_{\mathrm{A\,eq}}$	$L_{\mathrm{AF\,max}}$	L_{90}	L_{10}	Time exposure
Club 1	76.2	95.3	108.2	91.0	98.5	75
Club 2	78.0	96.8	112.2	88.9	100.4	90
Club 3	68.9	99.0	114.2	93.5	102.6	91
Club 4	70.6	95.5	110.8	85.4	99.4	89

In Club 3 the highest noise level was observed. For every measurement the statistical noise level L_{90} and L_{10} were calculated. The obtained results clearly indicated that in the Club 3 the highest noise levels were dominated during all time of the measurement duration. For the Club 4 the highest dynamics range of the noise level was observed. In the Club 1 the differences between L_{10} and L_{90} were the lowest. It means that the noise levels were concentrated near the average level.

In Fig. 3 the measured cumulative distributions of the noise levels were shown. The shifting of the cumulative curve of the Club 3 towards highest noise levels is noticeable. The shape of the curve for the Club 4 covers the widest range of the noise levels. For the Club 1 the curve has a steepest slope. In Fig. 4 the measured one-third octave bands noise levels for particular clubs were shown. For Clubs 2 and 3 the highest noise levels for the range of medium and high frequencies are observed. In the Club 1 the noise level was the lowest for high frequencies.

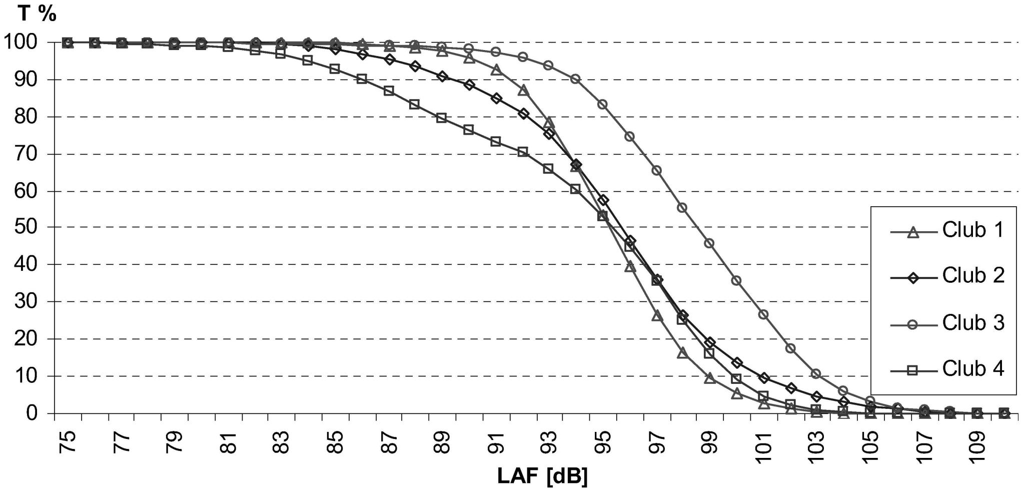

Fig. 3. Cumulative distribution of the noise levels for the clubs considered.

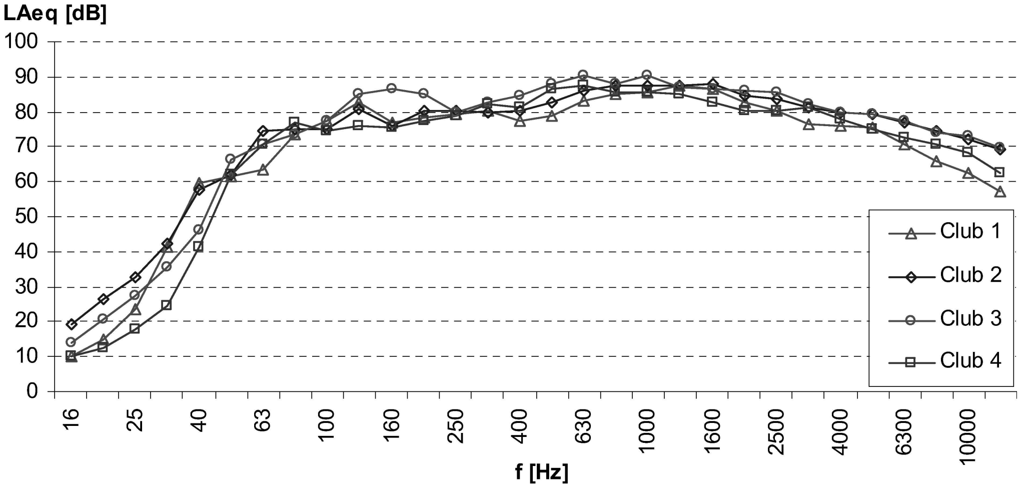

Fig. 4. $L_{\mathrm{A\,eq}}$ values in one-third octave bands obtained in clubs.

6.2. *Hearing measurement results*

The obtained hearing measurement results by means of the pure-tone audiometry are presented in Table 5. The average hearing threshold shift for particular audiometric frequencies is shown. 41 persons took part in hearing tests in all considered clubs, in Club 1–11 persons, in Club 2–9, in Club 3–12 and in Club 4–9 persons were examined. The highest TTS levels were observed for exposure in the Club 3. The lowest TTS changes occur after the noise exposure in the Club 1. For the 4 kHz the average hearing threshold shifts were the largest for all exposures. It is necessary to emphasize that the changes of the hearing threshold produced by noise have a large spread. It is confirmed by the computed minimum, maximum and standard deviation values. This means different sensitivity to noise of persons who took part in this study. In particular cases, TTS changes as large as 30–40 dB for 4 and 6 kHz have been noticed.

Table 5. Hearing measurement results obtained by means of the pure-tone audiometry for particular clubs. All values of hearing measurement results are expressed in dB HL.

	Freq [Hz]	1000	1500	2000	3000	4000	6000	8000
Club 1	Min	−10	−5	0	−5	−5	−15	−5
	Avg	0.5	4.75	7.25	10.5	**11**	5.25	2.25
	Max	15	15	20	25	30	20	15
	σ	6.9	6.4	6.2	8.4	9.8	10.3	6.2
Club 2	Min	0	–	−5	0	−5	−5	−20
	Avg	5.3	–	8.1	9.4	**13.1**	7.5	1.4
	Max	15	–	20	20	30	25	25
	σ	5.3	–	6.4	6.6	7.9	9.1	10.8
Club 3	Min	−5	−10	−5	0	−5	−5	−25
	Avg	3.6	7.3	10.2	12.3	**15.7**	12.5	−0.5
	Max	20	20	20	25	25	40	20
	σ	6.9	7.0	6.1	6.6	8.5	10.1	11.6
Club 4	Min	0	0	−5	0	0	−5	−15
	Avg	4.4	7.5	8.9	9.4	**13.9**	12.5	5.6
	Max	15	20	20	20	25	30	20
	σ	4.2	5.2	5.3	5.1	7.0	9.9	8.0

In Figure 5 statistical analysis results of the hearing threshold shift changes for particular clubs are shown. Values obtained before and after the noise exposure were compared. Most cases of the raising hearing threshold were observed for persons exposed to noise in the Club 4. The least negative changes in hearing threshold have been found for exposure in the Club 1. Additionally, the hearing examination was extended by employing the DPOAE method. In this way it is possible to determine the cochlea activity changes as a result of the noise impact using this method. In Figure 6 the measurement results are shown.

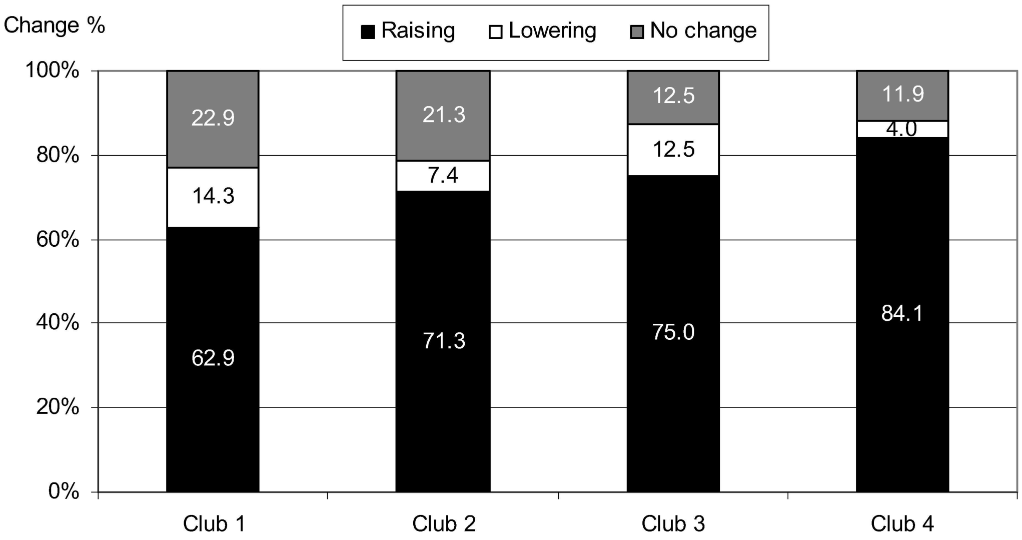

Fig. 5. Hearing threshold changes results for particular exposures obtained by means of the pure-tone audiometry.

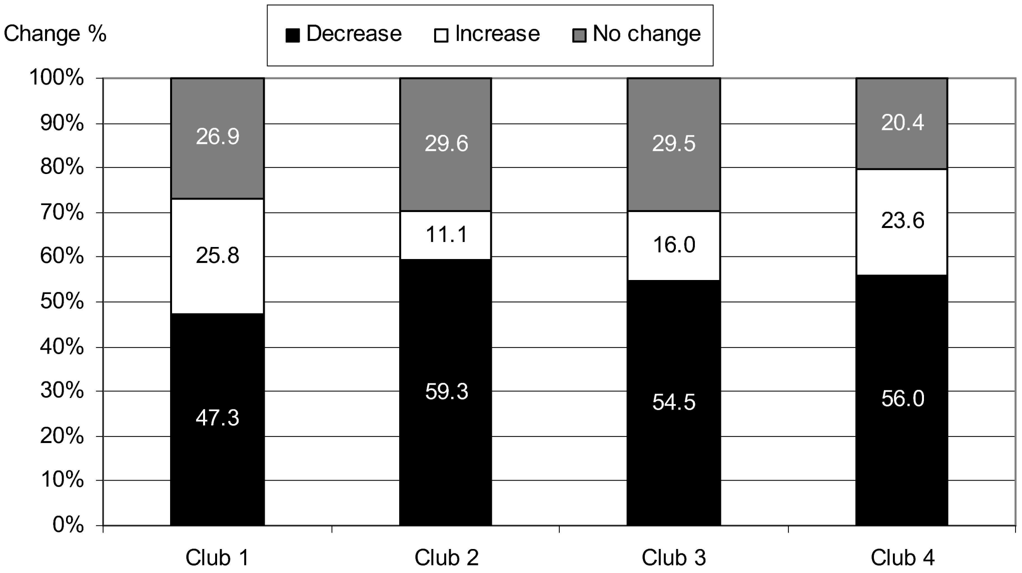

Fig. 6. Results of the hearing examination obtained by means of the DPOAE method. The average changes of the DP signal level for particular types of exposures.

The maximum degradation of the DP signal occurred for frequency where the highest TTS changes were observed using the pure-tone audiometry method. For every type of the exposure the decrease of the cochlea activity was observed. It means that the noise exposure affects the DP signal degradation. Statistically the most frequent cases of the decrease of the DP signal were affirmed for subjects staying in Clubs 2 and 4. In Figs. 7 and 8 a detailed analysis of the DP signal changes depending on frequency and the type of the exposure is shown.

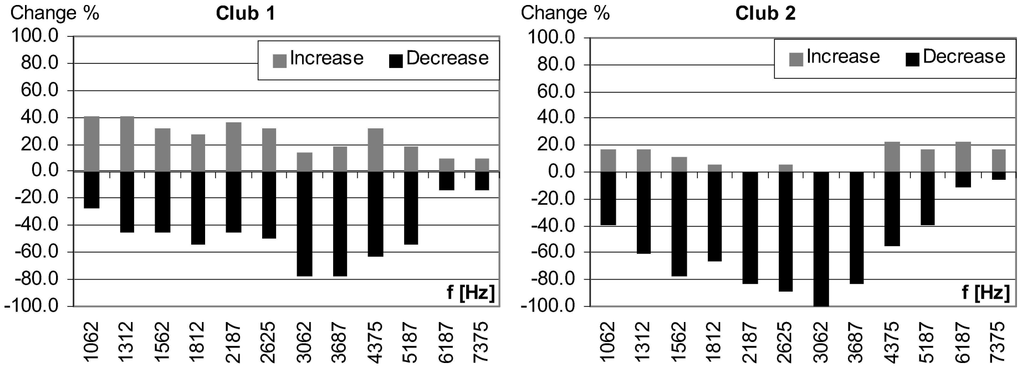

Fig. 7. The detailed changes of the DP test result for Clubs 1 and 2.

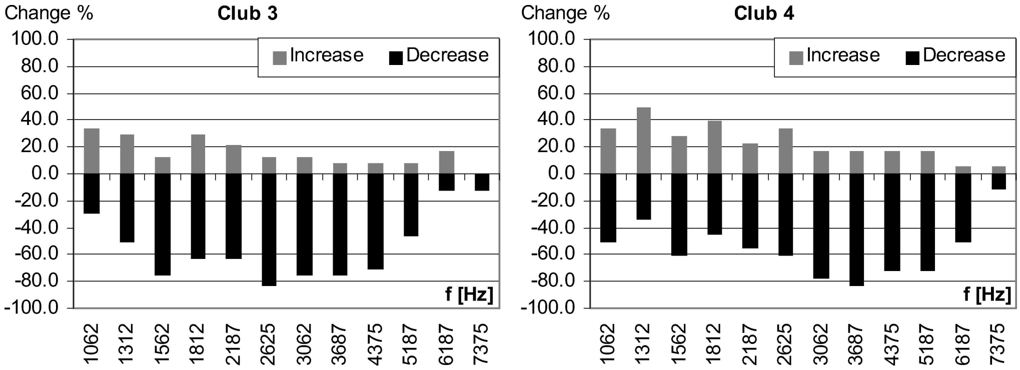

Fig. 8. The detailed changes of the DP test result for Clubs 3 and 4.

7. Evaluation of the psychoacoustical noise dosimeter in real exposure conditions

The obtained noise and hearing measurement results enabled to carry out the detailed verification of the designed psychoacoustical noise dosimeter (PND). This verification was done "off-line", after the end of the noise exposure. Such approach was necessary, the PND algorithm did not have the full functionality. The measurement results obtained in the acoustically controlled environment were used to optimize the PND algorithm performance, time constants for growing and recovery phases of the TTS effect were corrected according to results obtained. For computation of the hearing threshold shift for exposure in Clubs 1 and 3, the total $L_{\mathrm{A\,eq}}$ values for one-third octave band were used. For the noise measurements carried out in Clubs 2 and 4 a history of the $L_{\mathrm{A\,eq}}$ values in one-third octave band for one minute periods were known. It enables to perform more precise computations. In Figs. 9 and 10 the TTS levels obtained by means of the PND algorithm are presented. They were compared to the average values of the TTS obtained on the basis of the real hearing measurements. For the computed and measured TTS characteristics the Pearson's factor was calculated. The obtained results for all clubs are presented in Table 6. The value of Pearson's test is for the assumed confidence level equal 0.01.

Table 6. The calculated Pearson's factors for the computed and measured TTS characteristics.

	Club 1	Club 2	Club 3	Club 4	$\alpha = 0.01$
Pearson's test	0.814	0.882	0.931	0.813	0.789

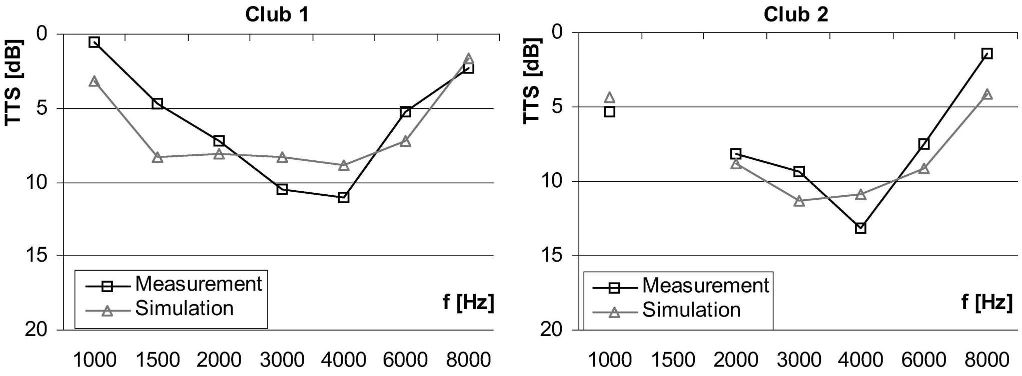

Fig. 9. TTS levels computed by means of the PND algorithm for exposure in Clubs 1 and 2.

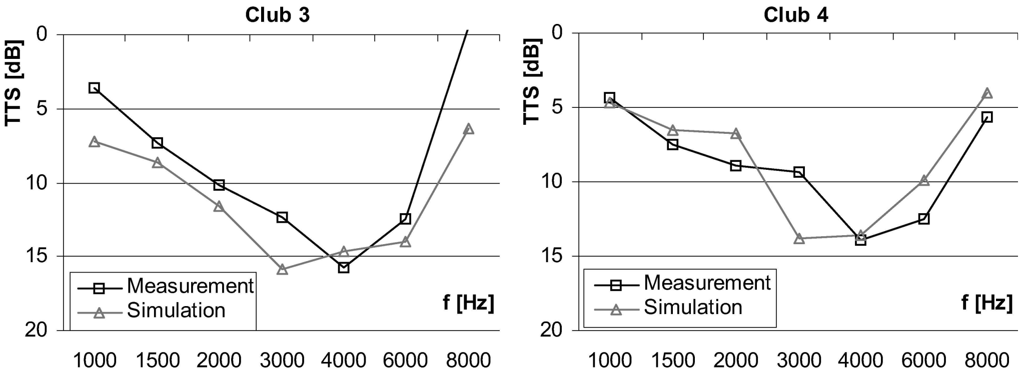

Fig. 10. TTS levels computed by means of the PND algorithm for exposure in Clubs 3 and 4.

On the basis of the analysis of the characteristics of the hearing threshold and taking into consideration the simulation results, it was ascertained that the PND algorithm correctly predict the average hearing threshold shift for a given type of noise. Additionally, the standard noise dose analysis was performed employing estimated $L_{\mathrm{A\,eq}}$ values [7]. The noise doses computed for particular clubs are shown in Table 7. The noise dose for the noise exposure in the laboratory condition is also listed in this table. For all considered clubs the obtained noise dose values significantly exceed the permissible daily noise dose. It is necessary to emphasize that the exposure duration amounted to 90 minutes. Typically, students spend much more time in music clubs. A short survey indicated that they usually spend approximately 225 minutes in a music club. Assuming that the noise climate in the given club is the same as during the measurements, the potential noise dose for such a case was calculated. In this case the daily noise dose was exceeded many times (for the Club 3 even 10 times!).

Table 7. The standard noise dose analysis results for considered type of exposure. The $L_{\mathrm{A\,eq}}$ is expressed in dB(A), time is expressed in minutes and noise dose in % (related to the permitted daily dose).

	$L_{\mathrm{A\,eq}}$	T meas.	Noise Dose	T typical	Noise Dose
Club 1	95.3	75	170	225	506
Club 2	96.8	91	289	225	716
Club 3	99.0	89	470	225	1191
Club 4	95.5	90	212	225	530
Laboratory	88.0	30	13	–	–

8. Conclusions

On the basis of the obtained results of the noise impact on hearing performed in the acoustically controlled environment the optimization of the PND algorithm was performed. The presented psychoacoustical noise dosimeter correctly determines the temporary threshold shift for the considered type of the noise exposure. A high conformity of the computed TTS values with the results of the real hearing measurements for all considered exposures in real conditions was observed. The designed and implemented algorithm owing to its functionality can have many practical applications in hearing conservation programs against occupational noise diseases. Information about the degree of the hearing threshold shift and its characteristics already got during noise exposure can significantly improve the effectiveness of the application of different occupational noise control methods. The computed parameters clearly present the noise impact on the human hearing system. On the basis of the performed examinations and analyses it was indicated that the acoustic climate in the considered clubs could be dangerous for people who stay in them. In all cases taken into consideration the daily noise dose was significantly exceeded. For the typical time spent by youth in a music club the exceeded dose is very remarkable (10 times for Club 3). Both the pure-tone audiometry and DPOAE tests unambiguously proved a serious reduction of the hearing sensitivity in persons exposed. The frequent staying in such acoustic environments could cause irreparable changes in the inner ear structure.

Acknowledgments

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