THE ADAPTATION OF NOISE-INDUCED TEMPORARY HEARING THRESHOLD SHIFT PREDICTIVE MODELS FOR MODELLING THE PUBLIC HEALTH POLICY

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Abstract

Objectives: It has been shown that monitoring temporary threshold shift (TTS) after exposure to noise may have a predictive value for susceptibility of developing permanent noise-induced hearing loss. The aim of this study is to present the assumptions of the TTS predictive model after its verification in normal hearing subjects along with demonstrating the usage of this model for the purposes of public health policy. **Material and Methods:** The existing computational predictive TTS models were adapted and validated in a group of 18 bartenders exposed to noise at the workplace. The performance of adapted TTS predictive model was assessed by receiver operating characteristic (ROC) analysis. The demonstration example of the usage of this model for estimating the risk of TTS in general unscreened population after exposure to loud music in discotheque bars or music clubs is provided. **Results:** The adapted TTS predictive model shows a satisfactory agreement in distributions of actual and predicted TTS values and good correlations between these values in examined bartenders measured at 4 kHz, and as a mean at speech frequencies (0.5–4 kHz). An optimal cut-off level for recognizing the TTS events, ca. 75% of young people (aged ca. 35 years) may experience TTS >5 dB, while <10% may exhibit

TTS of 15–18 dB. **Conclusions:** The final TTS predictive model proposed in this study needs to be validated in larger groups of subjects exposed to noise. Actual prediction of TTS episodes in general populations may become a helpful tool in creating the hearing protection public health policy. Int J Occup Med Environ Health. 2023;36(1):125–38

INTRODUCTION

Hearing loss is one of the most common chronic diseases especially among the elderly. According to the World Health Organization (WHO), disabling hearing loss affects about one third of people aged >65 years and >6% of the world population. These estimates do not include mild and unilateral hearing loss. The number of people affected by hearing loss is growing rapidly. In 2018 >466 million people suffered from disabling hearing loss, and its estimated number will increase to 900 million by 2050 [1].

Exposure to noise is one of the main causes of hearing loss in an increasingly ageing population. According to WHO, about 10% of the world's population is exposed to sound pressure levels that can potentially cause hearing loss [2]. Apart from industrial exposure to noise, this is increasingly due to exposure to non-occupational noise, e.g. entertainment noise, noise in rest areas, transport noise, or loud music listened through personal music players [3].

Noise-induced hearing loss (NIHL) caused by exposure to excessive sound pressure levels may occur due to one-time exposure to very high noise levels or due to prolonged exposure to noise at moderate sound levels. In the early stages of NIHL, permanent threshold shift (PTS) may be preceded by recurring incidents of temporary threshold shift (TTS) disappearing after cessation of exposure to noise. This was observed first in the 1960s [4,5], and confirmed by more recent work [6,7].

Although TTS recovers over time, reversible noise-induced incidents may trigger a progressive degeneration of auditory fibers and in consequence premature ageing of auditory organ resulting in speech communication difficulties [8,9]. This in turn affects the quality of life and level of social participation of hearing impaired people promoting their isolation and dementia development [10].

Since NIHL is an irreversible disease, its prevention must become priority. Regular audiometric testing allows to detect the first signs of NIHL, i.e., a notch in the audiogram at the high frequencies of 3000 Hz, 4000 Hz and 6000 Hz, and is used in monitoring hearing over the working lifetime in industry. Monitoring TTS incidents would also allow an early pharmacological intervention, if necessary.

Given the digitalization and technological advances, computerized TTS prediction models could be used to reduce the costs of testing actual TTS values in subjects at risk of NIHL. Computational TTS models were first described in the late 1970s [11,12], and then validated in the 1990s for people with normal hearing [13] and hearing-impaired subjects [14].

Under recently completed EVOTION project [15], a big data analytical information technology (IT) platform has been designed and developed as a tool for collecting and analyzing data on the usage of hearing aids (HA) by hearing impaired people for the purposes of developing public health policies. One of the public health policy decision model (PHPDM) developed under the project is forwarded to the prognosis and prevention of NIHL. In this study, existing mathematical predictive models of TTS have been refined throughout the EVOTION project based on categorizing the immediate risk of temporary hearing loss incidents due to environmental noise. One of the objectives of the EVOTION project was to develop tools to avoid NIHL formation in group of HA users, what can be achieved by monitoring, recognizing and report on hazardous sound levels impacting on ear. For this purpose,

a calculation model was prepared to link TTS size to noise exposure. It was assumed that any exposure to noise that leads to changes in hearing is dangerous. Therefore, any exposure to noise that may cause a temporary change in hearing in people with normal hearing can also be dangerous for hearing aid users, in other words, if the exposure is dangerous for people with normal hearing, it will also be dangerous for HA users. Specific aims of this study are:

– to prepare TTS predictive models adapted for modeling the public health policy by refining them throughout their checking in a group of bartenders exposed to genuine noise in discotheque bars and music clubs;
– to demonstrate the usage of the final TTS predictive model adapted for modeling the public health policy by estimating the risk of noise-induced TTS due to short exposure to loud music in the entertainment venues in the general unscreened population (database B4 from ISO 1999:2013).

MATERIAL AND METHODS

It has been assumed that the prognosis and prevention of NIHL will be based on a predictive model of TTS which should rely on monitoring the episodes of exposure to noise/sounds high enough to cause temporary changes to hearing lasting ≤16 h.

On the basis of available literature, an initial predictive computational TTS model was applied which was previously developed for normal hearing subjects by Mills et al. [11,12], and Melnick [13] and later adopted for hearing impaired people by Macrae [14,16].

Initial predictive model of TTS

The initial model of TTS used in this study takes into consideration the following variables: time of exposure to noise (or sounds) (in hours), A-weighted equivalent-continuous sound pressure level (in dB), and the actual audiometric hearing threshold of an exposed subject (in dB HL).

According to the model proposed by Mills et al. [11], the TTS due to noise exposure increases and reaches the maximum – so called asymptotic threshold shift (ATS) – after 8–10 h, whether the noise is stable or intermittent. When the exposure to noise ends, the HTs begins to return to the initial value (i.e., TTS decreases). Both the increase and decrease of TTS can be described by simple exponential functions (equations (1)–(4)).

If the exposure duration is less than that needed for the ATS, the TTS value to be expected at a given elapsed time (T) is described by the formula:

$$TTS_T = ATS \times \left(1 - e^{-\frac{T}{t_0}} \right) \tag{1}$$

where:
t_0 – the time constant equal to 2 h,
ATS – an asymptotic threshold shift.

Because after cessation of noise exposure, hearing threshold begins to return to its original value, the TTS at a particular recovery duration T is expressed by the equation:

$$TTS_T = ATS \times e^{-\frac{T}{t_0}} \tag{2}$$

where:
t_0 – the time constant equal to 7.2 h.

Since the main goal of this study is to monitor the hearing threshold shift, the latter formula was not included in the model of TTS.

Asymptotic threshold shift resulting from exposure to the 1/1-octave band f of noise (ATS_f) occurs about 1/2-octave above the center frequency of the band f and is given by the equation:

$$ATS_f = 1.7 \times \left\{ 10 \times \log \left[\frac{(I_{ef} + I_{cf})}{I_{cf}} \right] \right\} \tag{3}$$

where:

I_{ef} – the sound intensity of the 1/1-octave band f ($I_{ef} = 4 \times 10^{-10} \times 10^{Lef/10} \, Pa^2$),

I_{cf} – the critical sound intensity in the 1/1-octave band f ($I_{cf} = 4 \times 10^{-10} \times 10^{Lcf/10} \, Pa^2$),

L_{cf} – the critical sound pressure level in the 1/1-octave band, in dB.

Assuming that critical cut-off level for TTS is the lowest sound pressure level that causes a TTS ≥5 dB when the exposure is 16 h or longer, the L_{cf} levels in 1/1-octave bands are equal to: 74 dB at 4 kHz, 78 dB at 2 kHz and 82 dB at 1 kHz and 0.5 kHz.

In turn, ATS caused by broadband noise is calculated according to the following formula:

$$ATS = 1.7 \times \left\{ 10 \times \log \left[\frac{(I_e + I_c)}{I_c} \right] \right\} \qquad (4)$$

where:

I_e – the sound intensity for the broadband noise ($I_e = 4 \times 10^{-10} \times 10^{Le/10} \, Pa^2$ and L_e – the sound pressure level),

I_c – the critical sound intensity for the broadband noise ($I_c = 4 \times 10^{-10} \times 10^{Lc/10} \, Pa^2$),

L_c – the critical level for a broadband noise equal to 78 dB(A),

L_e – the sound pressure level [12].

Thus, the TTS resulting from exposure to a broadband noise can be calculated using the following equation:

$$TTS = ATS \times \left(1 - e^{-\frac{T}{t_0}} \right) =$$

$$= 1.7 \times \left\{ 10 \times \log \left[\frac{\left(10^{\frac{L_{Aeq,T}}{10}} + 10^{\frac{L_c}{10}} \right)}{10^{\frac{L_c}{10}}} \right] \right\} \times \left(1 - e^{-\frac{T}{t_0}} \right) \qquad (5)$$

where:

$L_{Aeq,T}$ – the A-weighted equivalent-continuous sound pressure level, in dB(A),

L_c – the critical level for a broadband noise equal to 78 dB(A),

T – time of exposure,

t_0 – the constant time equal to 2 h.

The aforesaid TTS model was developed and validated in young subjects with normal hearing [11–13]. It has been showed that TTS produced by a given noise exposure decreases as a function of the degree of pre-existing hearing loss [14].

For populations with the pre-existing sensorineural hearing loss, a specific model has been proposed. The amount of TTS in hearing impaired people could be predicted by means of a mathematical model consisting of the modified power law (MPL) of Humes and Jesteadt combined with equations for predicting TTS in listeners with normal hearing published by Mills et al. [11,12].

According to Macrae [14] TTS caused by noise exposure (at a particular audiometric frequency n) in HA users with sensorineural hearing loss can be predicted from the following equation:

$$TTS_{HL} = HL' - HL =$$

$$= 10 \times \log \left\{ \left[\left(10^{\frac{TTS}{10}} \right)^P + \left(10^{\frac{HL}{10}} \right)^P - 1 \right]^{\frac{1}{P}} \right\} - HL \qquad (6)$$

where:

TTS_{HL} – the predicted temporary threshold shift in the impaired ear,

HL – the initial pre-exposure hearing level of the impaired ear,

HL' – the shifted threshold in the impaired ear,

P – a constant equal to 0.2,

TTS – the temporary threshold shift that would be produced by the noise exposure in subjects with normal hearing.

When HL is equal to 0 the equation (6) gives the same result as s equation (5). The assumptions of the EVOTION project related to the scope of monitoring exposure to noise and temporary changes in hearing made it necessary to limit the amount of data on exposure to noise and TTS to monitor LA_{eq} and TTS for 4 kHz audiometric frequency, as a quantity characterizing exposure to noise and allowing for the identification of episodes hazardous to the ear. Therefore, models describing the magnitude of the exposure-dependent TTS in the octave bands were used, which was adapted to L_{Aeq} by adding parameters modifying the model. These parameters are related to the exposure characterizing L_{Aeq} and may depend on the technical parameters of the HA equipment used to monitor exposure to noise

The initial (basic) model for prediction of TTS has been based on equations (5) and (6) and was applied for TTS prediction in study group consisted of bartenders employed in discos, music clubs or pubs and appropriate modification were introduced into final model to fit TTS prediction to observed TTSs.

The participation in the study was voluntary. The subjects were recruited by advertisement. They obtained some remuneration and certified in writing their consent to participate in the research. The study design and methods were approved by the Bioethical Committee operating at the Nofer Institute of Occupational Medicine in Łódź (decision no. 14/201).

In order to verify and improve this initial TTS model, the actual post-exposure temporary hearing threshold shifts in volunteers working in noisy entertainment venues were compared with theoretical predictions. The study involved young bartenders who volunteered to participate in the study. None of them reported hearing problems. Hearing thresholds in all subjects were within 25 dB HL at the frequency range 0.25–8 kHz. Inclusion criteria were as follow: normal otoscopy, the lack of a history of chronic ear diseases no head injury, no exposure to ototoxic substances. There were 18 people included, 9 women and 9 men, aged 25±7 years, working in a music club (N = 8), disco club (N = 5) and pub (N = 5). Their time of employment ranged 1 month–6 years (average 13 months). Smoking was reported by 9 subjects.

Full-day measurement strategy according to PN-EN ISO 9612:2011 [17] was applied for evaluation of individual noise exposures at the workplace. The work shift among bartenders lasted 5–9 h, and a single measurement period lasted at least two-thirds of the work shift what meets requirements of the aforesaid standard. The sound pressure level measurements were carried out using the SVANTEK type SV104 noise dosimeters (Warsaw, Poland). These instruments were calibrated (with an appropriate adjustment if necessary) and checked (without adjustment) using the B&K type 4231 sound calibrator (Virum, Denmark) before and after each daily series of surveys. The noise dosimeters were mounted on the shoulders of bartenders with microphones located at a distance of 0.1–0.4 m from the entrance of the external ear canal.

The evaluation of TTS after noise exposure was based on the standard pure-tone air conduction audiometry (PTA). Hearing thresholds (HTs) were determined at frequencies: 0.25 kHz, 0.5 kHz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, 6 kHz and 8 kHz with a 2-dB steps using the VIDEOMED clinical audiometer type Audio 4002 (Szczawno Zdrój, Poland) equipped with the HOLMCO PD 81 headphones with earmuffs (Berlin, Germany). At least 15-hour time interval was maintained between the last exposure to noise at workplace and the hearing testing. Pure-tone air conduction audiometry was performed before and immediately after the end of work, during 2 or 3 sessions on weekends (Fridays and Saturdays). In total, 92 pre- and post-exposure audiograms (46 for the right ear and 46 for the left ear) were obtained. Differences significance between pre- and post-exposure HTs in bartenders was analyzed using the Wilcoxon signed-rank test.

The adapted TTS model was used to estimate the TTS risk due to exposure to loud music in the entertainment venues. The prediction was performed in the examined bartenders and in equivalent – in view of age and gender – unscreened population of an industrialized country which includes also subjects exposed to occupational noise (database B4 from ISO 1999:2013 [18]).

Based on results collected in the bartenders group, the initial TTS predictive model was amended by introducing appropriate multipliers modifying the results of the initially used formula. The relationships between actual TTS values observed in bartenders and TTS values predicted according to the initial and final (adapted) model were analyzed using Pearson's correlation coefficient (r). The distributions of actual and predicted TTS values were also compared using t-test, Mann-Whitney U test and Kolmogorov-Smirnov test.

In addition, the receiver operating characteristic (ROC) analysis was used to evaluate the performance of the final version of TTS model. The ROC curve describes the sensitivity and specificity of the decision criterion depending on the value of the variable classifying cases into different categories. Based on the ROC curve, optimal values of the classification to assess the effectiveness of the decision criterion were determined.

The Statistica v. 12 (StatSoft, Inc.) with Medical Set v. 3.0 (StatSoft Polska Sp. z o.o.) was used for statistical analysis. All tests were conducted with assumed significance level p < 0.05.

RESULTS

TTS in bartenders

Results of noise measurements carried out among bartenders at discos and music clubs are presented in Table 1. The A-weighted equivalent-continuous SPLs varied 76–100 dB(A). During over three-quarters of the tests sessions, study subjects were exposed to noise at the A-weighted SPLs levels exceeding the critical level for a broadband noise equal to 78 dB(A), while individual daily noise exposure level ($L_{EX,8h}$) exceeded the Polish maximum admissible intensity value ($L_{EX,8h}$ = 85 dB(A)) in more than half of analyzed cases.

Table 1. Summary results of 64 dosimetric noise measurements carried out among bartenders and Polish maximum admissible intensity (MAI) values in all studied music clubs, pubs and discotheques, Poland

Descriptive statistics	Sound pressure level (SPL) [dB]		
	$L_{Aeq,T}$	L_{Amax}	L_{Cpeak}
Minimum	67.6	85.3	112.5
Percentile			
10	75.9	93.1	116.5
25	82.1	100.3	119.5
50	89.5	104.2	125.8
75	95.6	109.8	132.3
90	100.1	114.7	136.0*
Maximum	108.7	117.4*	153.4*
Polish maximum admissible intensity (MAI) values	$L_{EX,8h}$ = 85	115	135

$L_{Aeq,T}$ – A-weighted equivalent-continuous sound pressure level; L_{Amax} – A-weighted maximum sound pressure level; L_{Cpeak} – C-weighted peak sound pressure level;
$L_{EX,8h}$ – A-weighted daily noise exposure level, i.e., the A-weighted equivalent-continuous sound pressure level normalized over 8-hour working day.
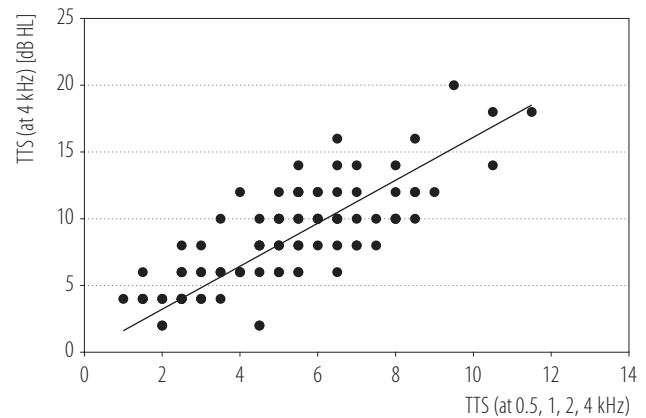* SPLs exceeding Polish MAI values.
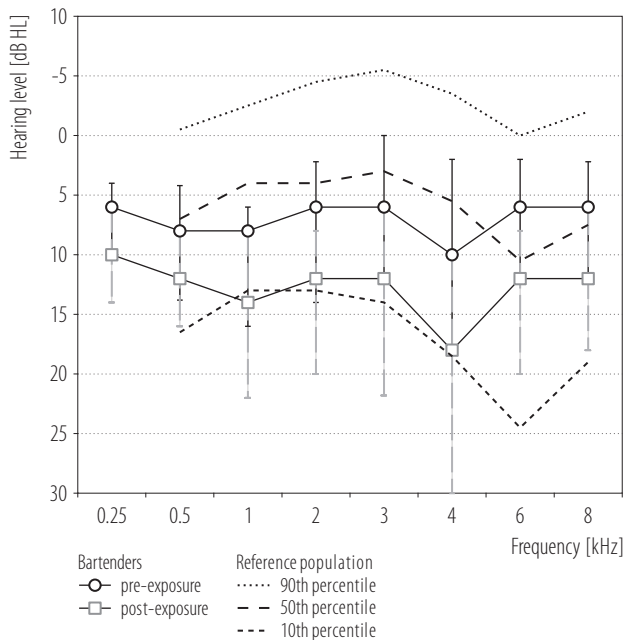
Figure 1. Distributions of pre- and post-exposure hearing thresholds (HTs) in bartenders compared to distribution of HTs in equivalent – in view of age and gender – reference unscreened population (database B4 from ISO 1999:2013 [17])

Figure 2. The relationship between observed temporary threshold shift (TTS) values at 4 kHz and mean values at 0.5, 1, 2 and 4 kHz in bartenders exposed to noise

Figure 1 presents pre- and post-exposure audiograms in bartenders against the distribution of expected hearing thresholds in equivalent – due to age and gender – reference unscreened population of an industrialized country (database B4 from ISO 1999:2013 [18]). Median pre-exposure HTs in bartenders are slightly worse at the frequency range 1–4 kHz than the median values in the reference population, but the differences are not statistically significant.

Statistical analysis (using the Wilcoxon signed-rank test) showed significant differences between pre- and post-exposure audiograms measured in bartenders for both ears at all frequencies (p < 0.0001) (Figure 1). The actual TTSs ranged 2–22 dB. In 14 of 18 (77%) subjects, TTS >10 dB was noted during at least one measurement session. The highest TTS values were observed in the frequency range 3–6 kHz which is typical for noise-induced hearing loss. A linear relationship was found

between observed TTS values at 4 kHz and mean TTS values at 0.5 kHz, 1 kHz, 2 kHz and 4 kHz (Figure 2).

Adaptation of the TTS predictive model

In the case of tests performed in real groups, PTS were observed. It was assumed that subject's hearing is in normal state if the their hearing threshold shift is ≤30 dB HL in any audiometric frequency. Using formula (6) of the initial TTS predictive model, a linear correlation was observed between actual values of TTS measured in bartenders and the TTS values predicted based on the measured SPLs, both for mean hearing thresholds at 0.5 kHz, 1 kHz, 2 kHz and 4 kHz and for 4 kHz (Figure 3a and 3b; values marked as [o]). However, the predicted values of TTS were about 3 times greater than actual TTS values.

Thus, in order to achieve better consistency between predicted and observed TTS values, the initial TTS predictive model was amended, i.e., appropriate multipliers (equal to 1/4 and 1.61/4 respectively for mean at frequency 0.5 kHz, 1 kHz, 2 kHz, 4 kHz and at frequency 4 kHz) modifying results of the formula (6) were introduced.

The above modifications were made based on the correlation analyses between the observed and predicted

a)

b)
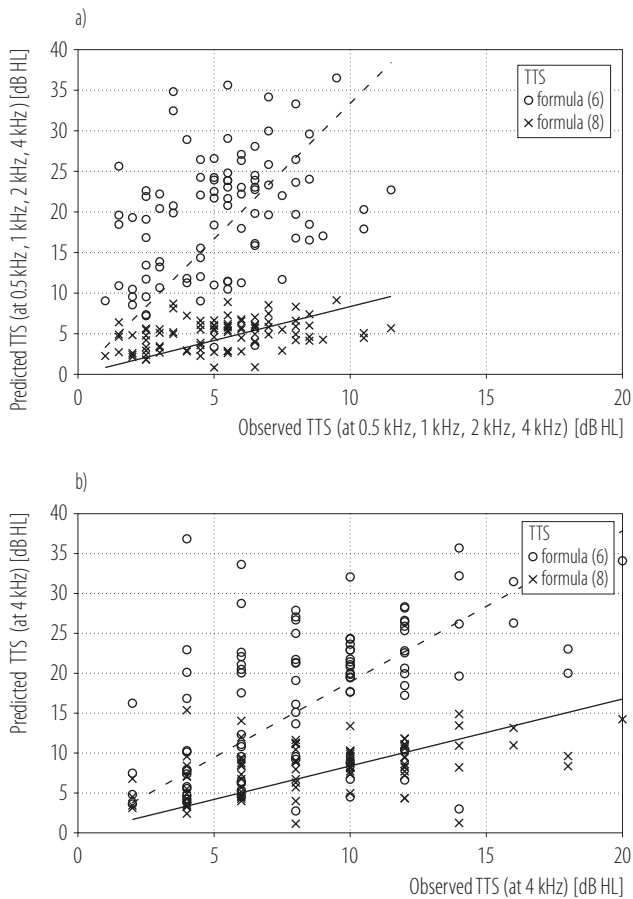
Figure 3. The relationships between temporary threshold shift (TTS) values observed in bartenders after exposure to noise and TTS values predicted according to the initial TTS predictive model according formula (6) and adapted TTS predictive model: a) according to formula (7) for mean hearing threshold at 0.5, 1, 2 and 4 kHz, b) according to formula (8) for hearing threshold at 4 kHz

TTS values calculated according to the different models described using equations (6)–(8). The model with the highest correlation and the best agreement between the distributions for the observed and predicted TTS values was selected as adapted model.

Consequently, in the adapted TTS predictive model, mean TTS at 0.5 kHz, 1 kHz, 2 kHz and 4 kHz ($TTS_{0.5–4 kHz}$) as well as the TTS at 4 kHz ($TTS_{4 kHz}$) can be estimated according to formulas (7) and (8):

$$TTS_{0.5–4 kHz} = TTS_{HL0.5–4 kHz} \times \frac{1}{4} \qquad (7)$$

$$TTS_{4 kHz} = TTS_{HL 4 kHz} \times \frac{1.61}{4} \qquad (8)$$

A linear correlation was observed between actual values of TTS measured in bartenders and calculated according to formula (6) and (7), for both mean hearing thresholds at 0.5 kHz, 1 kHz, 2 kHz and 4 kHz and hearing threshold at 4 kHz. Moreover, the predicted TTS values were similar to the actual TTS values measured in bartenders (Figure 3a and 3b; values marked as [×]).

The adapted TTS predictive model, like its initial version, takes into account the following variables:

– current pre-exposure audiometric HTs of an exposed subject (in dB HL),
– time of exposure to noise (in minutes or hours),
– the A-weighted equivalent-continuous sound pressure level of ambient sound measured close to the entrance to the external ear canal.

Table 2 shows the basic results describing the correlations and conformity of the observed and predicted TTS values using equations (6) in case of the initial model, and equations (7) and (8) in case of the adapted model. The Pearson correlation coefficients between the actual and predicted values both for the average TTS calculated at 0.5, 1, 2, 4 kHz, and for the TTS at 4 kHz are higher for model (7) than model (6), and higher for model (8) than model (6), respectively. No statistically significant differences were detected between the observed and calculated TTS values (Mann-Whitney U test, p > 0.05).

The distributions of actual and predicted TTS values at 4 kHz are presented in Figure 4, showing satisfactory agreement between these values.

ROC analysis for the final version of TTS predictive model

Generally, the purpose of ROC analysis is to find a decision criterion that maximizes the sensitivity and specificity of the decision method, which in this case is the recognition of actual TTS based on adapted TTS predictive

Table 2. Pearson correlation coefficients (r) between observed and predicted TTS values according to the different TTS predictive model in bartenders assuming pre-exposure hearing thresholds (HTs) >0 dB (equations 6, 7 and 8)

Predicted TTS based on the pre-exposure HT	Pearson correlation coefficients (r)[a]	
	mean TTS observed at 0.5 kHz, 1 kHz, 2 kHz, 4 kHz	TTS observed at 4 kHz
0.5, 1, 2 and 4 kHz	between observed and predicted according to formula (6) r = 0.34 [Z = 9.24, p < 0.0001]	between observed and predicted according to formula (7) **r = 0.47 [Z = −1.53, p = 0.13]**
4 kHz	between observed and predicted according to formula (6) r = 0.38 [Z = 8.96, p < 0.0001]	between observed and predicted according to formula (8) **r = 0.47 [Z = 1.46, p = 0.14]**

All (r) values are statistically significant (p < 0.05).
[Z, p] show results of the U Mann-Whitney test comparing predicted and observed TTSs.
The bold characters show the highest correlation coefficients (r) between observed and calculated TTS and marks agreement between observed and predicted TTS distribution.
[a] U Mann-Whitney test.

Table 3. Receiver operating characteristic (ROC) curves analysis for temporary hearing threshold shift (TTS) values at 4 kHz predicted according and adapted to the model and actually observed in the group of bartenders
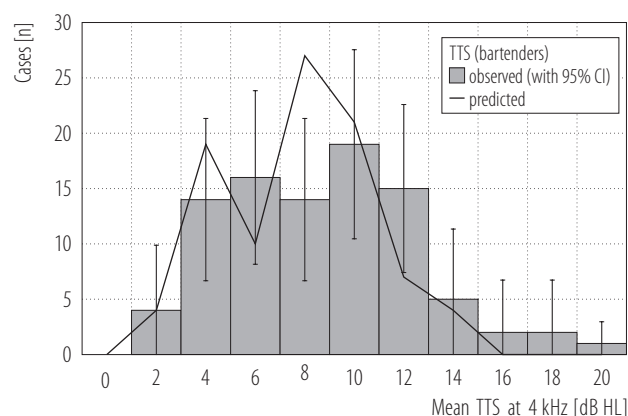
Description	AUC	95% CI	p
Probability of the correct TTS recognition*	0.805	0.678–0.932	<0.0001

AUC – area under curve.
* The ability of model (formula 8) to distinguish between classes with and without TTS ≥5 dB HL.

Figure 4. Distribution of temporary hearing threshold shift (TTS) values at 4 kHz observed in bartenders after exposure to noise and predicted according to the adapted TTS predictive model according to formula (8)

model. Results of this analysis are presented in Table 3 and Figure 5. The area under the curve (AUC) in Figure 5 is a measure of how well a final model can or cannot predict the actual TTS values.

Depending on the assumed criterion of the TTS occurrence it is possible to determine different cut-off points. An optimal cut-off level, maximizing the sensitivity and specificity of the prediction has been established at 6.9 dB HL. In such case, the sensitivity of identifying actual TTS events is 77%, which means that 23% of cases are omitted (false negative results), while the specificity is 83%, which means that 17% of cases are false positive. Since hearing protecting from its further deterioration due to noise exposure in case of HAs' users is one of the main aims of the EVOTION platform, the decision

criterion for monitoring the TTS episodes should determine the greatest possible number of actual TTS cases, what can be achieved by decreasing the cut-off value. Setting the TTS cut-off value to 3.8 dB increases the fraction of correct identification of actual TTS up to 97%, but simultaneously also increases the number of false positive recognitions of TTS events (up to 39%) (Figure 5).

For the EVOTION platform purpose a 5 dB cut-off point was adopted. The TTS identification rule with such cut-off value has a sensitivity of 84% and a specificity of 66% as well as a Youden's index of 0.5. Although the predic-
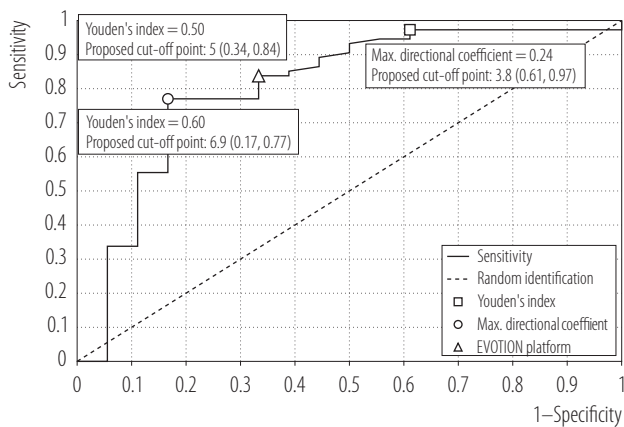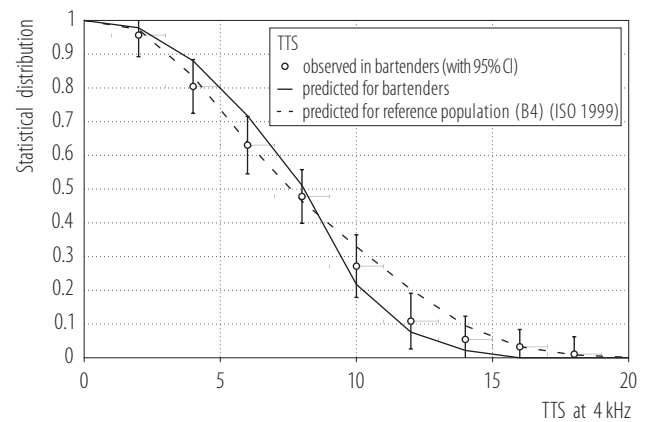
Figure 5. Receiver operating characteristic (ROC) curves for TTS values at 4 kHz predicted according to the adapted model according to formula (8) and actually observed in the study group of bartenders

Predictions were performed for bartenders and equivalent – due to noise, age and gender – unscreened reference population (database B4 from ISO 1999:2013 [18]) based on noise levels collected in this study (Table 1).

Figure 6. Predicted risk of occurrence of temporary hearing threshold shift (TTS) at 4 kHz after exposure to loud music (noise) in discotheque bars or music clubs together with statistical distribution of actual TTS at 4 kHz determined in the examined bartenders

tive value of the decision rule loses its quality (more false positive cases), the implementation of this cut-off value enables to recognize more cases with actual TTS.

Risk assessment of TTS

The adapted TTS predictive model can be used to assess the risk of TTS occurrence in any selected populations exposed to noise during various types of activities, e.g., entertainment. Figure 6 presents an example of analysis of the risk of TTS among young people (aged ca. 35 years) due to exposure to loud music (noise) in discotheque bars or music clubs.

It was assumed that people were exposed to noise at similar sound pressure levels as those measured in the group of bartenders (Table 1). The TTSs at 4 kHz have been determined according to the adapted TTS predictive model (taking into account equation (8)). These calculations were carried for bartenders and equivalent (due to age and gender) unscreened population (database B4 from ISO 1999:2013 [17]). Their results are presented together with statistical distribution of actual TTS values measured in examined bartenders. According to the graph, ca. 75% of young people (aged ca. 35 years) attending discotheque bars or music clubs may experience TTS >5 dB,

while <10% of them may exhibit TTS between 15–18 dB. For example, such TTS may occur after a 6-hour exposure to noise at the A-weighted equivalent continuous SPL of 92–94 dB(A).

DISCUSSION

This research was aimed at adaptation of the known TTS predictive models for the needs of the hearing public health policy, as it is believed that monitoring of TTS episodes may be helpful in preventing of the permanent hearing loss due to overexposure to noise.

Temporary threshold shift incidents are quite common in everyday life. As it was shown in the group of bartenders examined in this study, in 77% of exposed individuals the TTS values observed after the work shift were at or above 10 dB. A similar percentage of young people exposed to loud music at entertainment venues, namely DJs [20] as well as users of personal music players [21], might be at risk of developing TTS.

Temporary threshold shift testing in occupational setting has a long history, since in the 1970s and 1980s of

the last century in some countries it was performed in workers prior to the employment at noisy workplaces. It was speculated that the magnitude of notch at 4 kHz after acute low frequencies exposure may predict worker's susceptibility to a permanent NIHL. It was also believed that TTS values <30 dB (measured 2 min after exposure) are fully reversible, and HTs come back to normal within 16 h, while "pathological" TTSs ≥40 dB are critical for promotion of permanent changes in hearing.

The mathematical predictive model of TTS that has been explored in this study was first described by Mills et al. [11]. By measuring TTSs in 60 humans exposed in a sound field to octave band noise for 16–24 h, the authors showed that TTS increased for about 8 h and then reached a plateau or asymptote. The relation between TTS and exposure duration could be described by a simple exponential function. Critical levels for TTS were empirically estimated to be 74 dB SPL at 4 kHz, 78 dB at 2 kHz, and 82 dB at 1 kHz and 0.5 kHz. After termination of the exposure, recovery to within 5 dB of pre-exposure thresholds was achieved in ≤24 h.

In 1981, the same group of researchers [12] verified their original predictive TTS model in a group of 42 subjects exposed in a sound field to a wideband noise centered at 0.5 kHz, 1 kHz, 2 kHz, and 4 kHz for 24 h or 8 h on consecutive days. For the 24-hour exposure, TSS increased for about 8 h and then reached a plateau or asymptote in noise level above approx. 78 dB(A). Acceptably accurate predictions were achieved when the TTS produced by single-octave band exposures model was used to predict the TTS produced by the wideband noise exposures.

Melnick [13] analysed the results of ATS research and the studies on noise at the SPLs low enough (effective silence) not to induce TTS. He concluded that the increase in TTS reaches an asymptote (ATS) after 8–10 h of noise exposure, regardless of whether it is constant or intermittent. Both growth and recovery are described by simple exponential functions. Moreover,

he showed that the studies of both effective silence and ATS provided similar estimates of noise levels, which may pose a risk to hearing. For broadband noise, the estimate from the effective silence method is 76 dBA, while the ATS studies indicate that the level is 78 dBA. Thus, the critical level for a broadband noise equal to 78 dBA has been established for the purposes of this study.

Macrae [14,16] used the mathematical model described by Mills et al. [11,12] to predict ATS in people with hearing loss using hearing aids. In addition to original formula, the MPL was used to derive safety limits for TTS. Macrae [16] investigated the accuracy of the predictive TTS model in a small group of 9 subjects with hearing loss and showed that the MPL combined with equations for predicting TTS was the listeners' normal result in good prediction of TTS in hearing impaired subjects if the exponent p = 0.20 (instead of p = 0.15) (formula (6)). Having considered the publications cited above, this study offered a model which makes TTS dependent on the L_{Aeq} level of broadband noise to which the investigated workers are exposed. The authors adapted the model originally described by Macrae [16] as formula (6) in a group of 18 bartenders. Although the levels of noise at their workplaces, estimated as A-weighted daily noise exposure level, i.e., the A-weighted equivalent-continuous sound pressure level normalized over 8-hour working day – $L_{EX,8h}$, exceeded allowable Polish limits (MAI), the investigated subjects have not got into a habit of using hearing protectors.

The authors showed that the original mathematical model described by Macrae [16] in formula (6) overestimated actual values of TTS measured in bartenders (Figure 3) for both averaged TTS at frequencies 0.5 kHz, 1 kHz, 2 kHz and 4 kHz, and for the single frequency of 4 kHz. Hypothetically, the reason for that is that the original model was derived according to the investigation related to 4 octave frequency bands (0.5 kHz, 1 kHz, 2 kHz and 4 kHz), and not for the broadband noise levels measured

in this study. Thus, to adjust the original TTS predictive model formula to the results received in bartenders, a divisor of 4 was introduced to equation (6) to describe the mean TTS at frequencies 0.5 kHz, 1 kHz, 2 kHz and 4 kHz. Furthermore, to predict TTS at a single frequency of 4 kHz, equation (6) has been refined by adding a value of 1.61, which represents the correlation coefficient of the relationship between the actually observed TTS at 4 kHz and average TTS at 0.5 kHz, 1 kHz, 2 kHz and 4 kHz (Figure 2). The refinements for the original TTS predictive model formula described for frequencies 0.5 kHz, 1 kHz, 2 kHz and 4 kHz and for a single frequency of 4 kHz are proposed as equations (7) and (8), respectively.

The TTS predictive model in this study fits much better the actually measured TTS values in bartenders than the original model (Figure 3). It explains 22% of variability against 14% of the original model (Table 2).

Since the 4 kHz frequency is most sensitive to acoustic trauma, in the EVOTION project, procedures were used to identify TTS appearing at 4 kHz, which determined the choice of the calculation model. The ROC curve method was used according to the ambient sound exposure monitoring and calculating the results according to the refined final TTS predictive model. This analysis confirmed the usefulness of the developed model for identifying TTS cases. Depending on the needs of the procedures used, it is possible to modify the sensitivity and specificity of the TTS cases identification method by changing the cut-off level. Its optimal value for recognizing the TTS events, maximizing the sensitivity and specificity of the model, was established at 6.9 dB HL. In that case, the sensitivity of identifying actual TTS events is 77%, which means that 23% of cases are omitted (false negative results), while the specificity is 83%, which means that 17% of cases are false positive.

As it was shown in literature, only TTS >30 dB are believed to promote PTS occurrence [19]. However, the afore-

said value was established for normal hearing subjects. In hearing impaired people, TTS decreases as the degree of hearing loss increases. According to equation (6), these values decline from 30 dB for the HT = 0 dB HL to 8 dB for HT = 40 dB HL and 2 dB for HT = 80 dB HL. In this study, none of the bartenders reported hearing problems, although the averaged HTs for the study group were slightly worse than in the general population equivalent in age and gender and unscreened for noise exposure. Temporary changes in hearing at 4 kHz ≥5 dB were observed in 75% of bartenders. The percentage of subjects with TTS decreased to 48% for the cases of TTS ≥8 dB and to 5% for the cases of TTS ≥14 dB.

When comparing the statistical distribution of predicted TTS values in general population and actual TTS values measured in bartenders at 4 kHz using formula (8), it could be noted that the risk (probability) of the prevalence of TTS >8 dB in the age and gender equivalent to unscreened population is higher than that observed in bartenders. For TTS >12 dB, the estimated risk in the unscreened population is about 2–3 times higher than in bartenders (Figure 6). This is largely explainable by the fact that the bartenders' hearing was worse than that of the general unscreened population, thus potential values of TTS were lower. Although TTS prediction in this example is based on the 4 kHz frequency, similar calculation procedure may be applied for the average TTS at speech frequencies (0.5, 1, 2, and 4 kHz), and used for anticipating and/or conducting analyses in general population for public health policy purposes.

The temporary shift of HTs is still under investigation, both in the studies conducted in humans under laboratory conditions [20] and in various environments, e.g., among people attending classes in fitness clubs [21], as well as in animals after exposure to impulse noise [22].

Major constraint of this study is a relatively insignificant number of subjects surveyed to verify the original TTS model. Indeed, the bartenders are young and have rela-

tively good hearing. However, the results of TTS in healthy people may be used to build a predictive model, assuming the following assumptions that safe exposure to noise should not cause any changes in hearing in people with normal hearing and that for HA users any exposure that is dangerous for people with normal hearing. It should be noted, however, that nowadays, for ethical reasons, it is not allowable to intentionally expose people to high levels of noise, as it was previously done by Mills et al. [11,12] and Macrae [16], and environmental exposures to noise are technically difficult to be monitored. The population of entertainment industry employees is exceptional for this reason, although monitoring the noise throughout the work shift is time consuming. More studies in these groups of workers are needed.

The proposed model does not take into account the influence of the impulsiveness of noise or other risk factors underlying individual susceptibility to noise, because their impact on the hearing status is too little known to build predictive models linking them with temporary changes in the HT.

Informative and predictive measurements, along with the provision of efficient and effective services, can form a holistic noise-prevention and safety strategy and provide a new way to assess the effect of the noise exposure impact on the overall well-being of a population. The authors assume that the Public Health Policy Decision Model, developed under the EVOTION project, using the adapted TTS predictive model described in this study can guide noise regulations, protocols, and preventive actions related to hearing safety.

CONCLUSIONS

The proposed final TTS computational model can be used to estimate the expected temporary changes in hearing caused by exposure to noise in various acoustic environments. The model can be applied to exposure in the work environment and in a broadly understood non-profes-

sional environment, and estimate the expected TTS for groups with different levels of hearing damage. Taking into account statistical distributions of sound levels and distributions of HTs' occurring in exposed populations, this model can be used to assess the risk of TTS occurrence with specific values, e.g., among employees of a particular plant or in a specific group of people exposed to noise in various places: at work, in sports facilities and means of transport.

The EVOTION platform containing a large database with SPL measurement results may become a helpful tool in creating hearing protection and public health policy.

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