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Theoretical Predictions and Actual Hearing Threshold Levels in Workers Exposed to Ultrasonic Noise of Impulsive Character—A Pilot Study

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Results of standard pure-tone audiom etry (PTA) were collected from 25 workers, mainly females, aged 23–58 years, exposed for 2–13 years to ultrasonic noise emitted by ultrasonic welders. Hearing tests were completed by evaluation of exposure to ultrasonic noise. The subjects' actual audiometric hearing threshold levels (HTLs) were compared with theoretical predictions calculated according to ISO 1999:1990. In 60% of cases sound pressure levels in the 10–40 kHz 1/3-octave bands at workstands exceeded Polish exposure limits for ultrasonic noise. Our comparison of predicted and measured HTLs suggests that the ISO 1999:1990 method, intended for audible noise, might also make it possible to predict reliably permanent hearing loss (in the 2 000–6 000 Hz frequency range) after exposure to ultrasonic noise. No significant progress of hearing impairment (assessed using PTA) in the operators of ultrasonic welders was noted. Nevertheless, further studies on the hearing status of workers exposed to ultrasonic noise are needed.

ultrasonic noise   noise measurements   pure-tone audiometry   hearing threshold levels

1. INTRODUCTION

Noise exposure is commonly regarded as the main hazard leading to occupational hearing loss. However, at many workplaces, there is broadband noise dominated by frequency content of high audible and low ultrasonic frequencies from 10 to 40 kHz, which is called ultrasonic noise.

Low-frequency ultrasonic technological devices, including washers, welders, drills, soldering tools and galvanising pots, may be listed as the main sources of ultrasonic noise in the occupational setting. It is also generated by compressors, pneumatic tools, high-speed machinery, such as planers, millers, grinders, circular saws and some textile machinery. Plasma-arc welding, air-acetylene welding, etc., also generate it [1, 2, 3, 4].

Ultrasonic noise and its effects are usually given less consideration than audible noise. First occupational exposure limits for airborne ultrasound (ultrasonic noise) were recommended by individual researchers in the 1960s. They were based on two basic principles. Very high frequency components (10–20 kHz) are capable of causing annoyance, tinnitus, headaches, fatigue and even nausea. On the other hand high-level ultrasonic components (above 20 kHz) are capable of causing damage to the hearing. Thus, limit values were proposed to eliminate any subjective or auditory effects in any exposed individuals [1, 5, 6, 7].

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Those tentative recommendations, supported by limited experimental and survey data, were taken up by many national and international bodies. Nowadays, many countries, including Poland, have standards on maximum admissible levels (Table 1) [1, 2, 8, 9]. However, no regulations on airborne ultrasound have so far been established in the European Union.

TABLE 1. Maximum Admissible Intensity (MAI) Values for Ultrasonic Noise [9]

1/3-Octave Band Frequency, f (kHz)	$L_{f,\,eq,\,8\text{-hr},\,adm}$ or $L_{f,\,eq,\,wk,\,adm}$ (dB)	$L_{f,\,max,\,adm}$ (dB)
10, 12.5, 16	80	100
20	90	110
25	105	125
31.5, 40	110	130

Notes. $L_{f,\,eq,\,8\text{-hr},\,adm}$—equivalent-continuous sound pressure levels in 1/3-octave bands, normalized to a nominal 8-hr working day, $L_{f,\,eq,\,wk,\,adm}$—equivalent-continuous sound pressure levels in the 1/3-octave bands normalized to a 40-hr working week, $L_{f,\,max,\,adm}$—maximum sound pressure levels in 1/3-octave bands.

Since the introduction of limits, there have not been much literature data showing a permanent threshold shift resulting from occupational exposure to ultrasonic noise [10, 11]. However, results of noise measurements performed in occupational settings indicate that sound pressure levels at many workplaces very often exceed Polish maximum admissible intensity (MAI) values for ultrasonic noise. In particular this is true for workplaces located in the vicinity of ultrasonic lace sewing machines and ultrasonic welders [2, 3, 4].

Ultrasonic welding is a method of joining two elements by converting electrical energy into heat with high-frequency mechanical vibration; it is suitable for plastics and metals. One part of the assembly is set in motion, whereas the other remains static. In this way there is intense friction between the two elements. Movement is provided with a vibrating component called a sonotrode, which is applied at right angles to the surface of the element to be welded. The vibration frequency of the sonotrode is usually 20–40 kHz.

Ultrasonic welding of thermoplastics causes local melting of the plastic due to absorption of vibration energy, while ultrasonic welding of metals occurs due to high-pressure dispersion of surface oxides and local motion of the materials. Generally, the weld times are relatively short (usually 0.1–1.5 s). Therefore, ultrasonic welders are sources of impulsive ultrasonic noise.

The aim of this study was to assess hearing status in operators of ultrasonic welding machine who are exposed to ultrasonic impulsive noise. Another objective was to compare actual audiometric hearing thresholds with theoretical predictions calculated according to Standard No. ISO 1999:1990 [12].

2. MATERIALS AND METHODS

The study involved 25 workers, mainly females, aged 23–58 years (M = 46.2 ± 11.7). They had worked in one factory as operators of ultrasonic welders for 2–13 years. In this factory, ultrasonic welding machines were used in the process of manufacturing filtering respirators.

For each subject, results of standard pure-tone audiometry (PTA), performed at regular intervals within the framework of obligatory preventive medical examinations, were collected.

Hearing threshold levels (HTLs) for air conduction were determined at frequencies of 250, 500, 1 000, 2 000, 3 000, 4 000, 6 000 and 8 000 Hz using an ascending–descending technique in 5-dB steps. Examinations were performed by local occupational medicine staff in a sound-proof room.

Additionally, all workers were interviewed using a questionnaire with questions on (a) age, education, workstand, tenure; (b) past and present exposure to noise; (c) sensations and complaints subjectively related to exposure to noise at the current workstand; (d) the rating—on a 100-point graphical scale—of loudness and annoyance caused by noise at the workstand; and (e) self-assessment of the hearing status.

In order to evaluate workers' current exposure to ultrasonic noise, equivalent-continuous ($L_{f,\,eq,\,T}$) and maximum ($L_{f,\,max}$) sound pressure levels (SPLs) in 1/3-octave bands from 10 to 80 kHz were determined using a measuring system consisting of a Brüel & Kjær (Denmark) B&K 4138 or 4938 microphone, a B&K 2639 microphone preamplifier, and a B&K 2131 real-time frequency analyzer with a B&K 5765 expansion unit.

Linear averaging was applied to determine the $L_{f,\ \mathrm{eq},\ \mathrm{T}}$ levels, while exponential averaging (with time constants of 1 s) was used for the $L_{f,\ \mathrm{max}}$ values. Since ultrasonic welders produced single impulses of ultrasonic noise with more or less regular technological breaks between them, the measurements included a known number of welds and breaks over a fixed period of time (at least 5×64 s). Thus, the effective exposure time was the duration of measurement multiplied by the number of welds per day divided by the number of welds in the measurement period.

The surveys were done under typical conditions of work and with reference to Standard No. ISO 9612:1997 [13]. As in all cases a worker's presence was necessary to operate a welder, the microphone was located close to his or her head, approximately 0.10 m from the entrance of the external canal of the ear receiving the higher value of sound pressure level in the 1/3-octave band corresponding to the nominal frequency of the welder. Particular attention was paid to ensure that the microphone was arranged in the direction of sight of the person occupying this workstand as well towards the sonotrode to find out the dominant direction of the emitted ultrasound (Figure 1).

To obtain information on previous conditions of noise exposure, the records of the authors' measurements in that factory during the past 6 years were explored.

Potential hearing impairment in workers exposed to ultrasonic noise was analyzed using the differences between the PTA results obtained during the first and last hearing tests. Additionally, the actual (last) audiometric HTLs were compared with hearing losses predicted according Standard No. ISO 1999:1990 [12].

Differences between last and first PTAs were analyzed using Wilcoxon's matched pairs test, while the predicted and actual HTLs were compared with the Mann–Whitney *U* test. The statistical analysis was done using StatSoft's Stasistica version 6.1 ($p < .05$).

Standard No. ISO 1999:1990 [12] specifies the method for calculating noise-induced permanent threshold shift (NIPTS) of adult populations following exposure to noise. It assumes that HTL is a combination of HTL shift associated with age (HTLA) and occupational exposure to noise (NIPTS), and therefore makes it possible to determine distribution of noise-induced hearing loss in noise-exposed population based on four parameters: age, gender, and level and duration of noise exposure (in years).

Thus, in order to determine NIPTS in welder operators, the authors attempted to evaluate operators' exposure to noise over total tenure, including past and present workplaces. It was rather difficult to accurately determine noise exposure levels related to ultrasonic welders, since workers shifted from one workstand to another as required. Moreover, in the factory where the study was conducted, exposure varied over time due to the introduction of new machines, technological

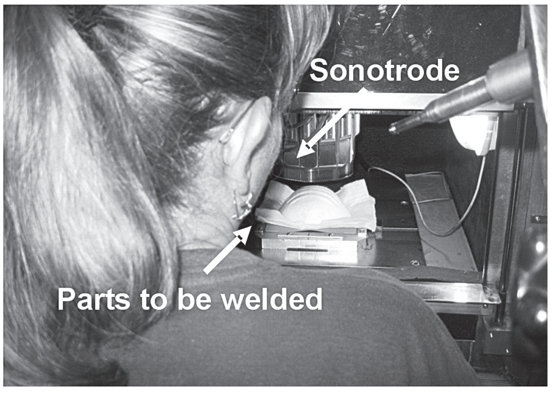

Figure 1. Location of the microphone during ultrasonic noise measurements.

or organization changes, etc. Therefore, instead of operators' individual levels, the distribution of noise exposure level (normalized over an 8-hr working day) $L_{EX,\ 8\text{-hr}}$ occurring at ultrasonic welders' workstands was determined. On the other hand, workers' exposure to noise at previous workstands was estimated from questionnaire data.

In consequence, for each subject predicted NIPTS was calculated repeatedly (1 000 times) using the actual values of gender, and duration and level of noise exposure determined from data randomly selected from the obtained distribution of $L_{EX,\ 8\text{-hr}}$ at welders' workstands. The final result for individual workers was retrieved from the distribution of the results of the repeated calculation.

3. RESULTS

3.1. Noise Exposure

Results of recent measurements performed at 25 workstands of ultrasonic welder operators are summarized in Table 2. Generally, measured equivalent-continuous sound pressure levels in the 1/3-octave bands from 10 to 40 kHz exceeded admissible values for 8-hr exposure (MAI values for ultrasonic noise) in 72% of cases under study. However, after taking into consideration the effective time of exposure to ultrasonic noise, excessive MAI were noted at 60% of workstands. Moreover, in almost half (48%) of welders, the recorded sound pressure levels also exceeded the admissible values of maximum SPLs in the 1/3-octave bands.

Results of ultrasonic noise measurements (n = 90 cases) performed within the past 6 years are presented in Figure 2. The equivalent-continuous sound pressure levels in the 1/3-octave bands (normalized to a nominal 8-hr working day) and maximum SPLs within the 10–40 kHz frequency range exceeded MAI values for ultrasonic noise in 50 and 10.8% of the cases under study, respectively.

To make prediction of noise-induced permanent threshold shift in accordance with Standard No. ISO 1999:1990 [12] possible, noise exposure

TABLE 2. Sound Pressure Levels Measured at 25 Workstands of Welder Operators (Range, *M* ± *SD*)

1/3-Octave Band Frequency, f (kHz)	f_o = 20 kHz		f_o = 31.5 kHz	
	$L_{f,\ eq,\ 8\text{-hr}}$	$L_{f,\ max}$	$L_{f,\ eq,\ 8\text{-hr}}$	$L_{f,\ max}$
10	53–76 66.9±7.4	60–92 76.5±10.3	58–78 66.8±6.0	70–82 74.8±4.8
12.5	57–76 70.5±7.2	64–90 80.5±9.0	57–76 65.5±5.9	70–83 75.3±5.0
16	75–95 88.0±6.9	84–108 99.2±8.4	57–88 70.9±8.6	70–101 84.8±9.2
20	88–113 105.7±9.6	97–128 117.0±10.8	59–106 79.9±15.3	71–120 91.3±16.0
25	65–90 81.9±9.4	79–110 99.2±11.0	70–88 80.1±5.6	90–104 97.8±4.6
31.5	56–87 73.7±9.7	69–106 90.3±12.3	95–114 105.6±5.7	115–130 123.6±4.6
40	67–103 90.1±11.5	81–124 107.7±14.8	94–112 103.5±5.5	115–128 121.4±4.4
Times MAI values were exceeded, n	9	9	6	3
Total number of cases, N	11		14	

Notes. f_o—operating frequency of ultrasonic welders within 1/3-octave bands, $L_{f,\ eq,\ 8\text{-hr}}$—equivalent-continuous sound pressure levels in the 1/3-octave band normalized to a nominal 8-hr working day, $L_{f,\ max}$—maximum sound pressure levels in the 1/3-octave band, MAI—maximum admissible intensity.

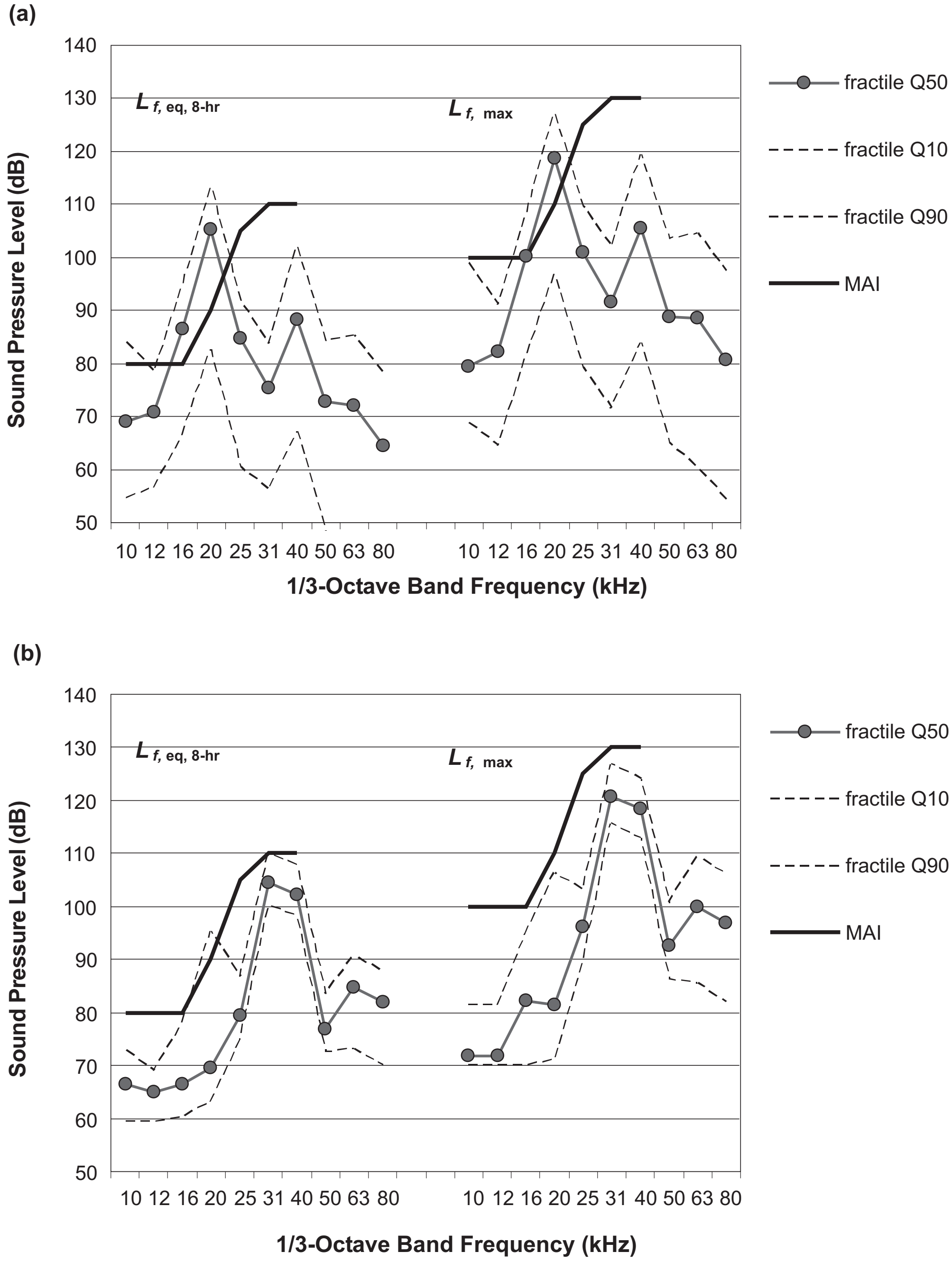

Figure 2. Ultrasonic noise generated by ultrasonic welders of nominal operating frequency within the 1/3-octave band of (a) 20 kHz and (b) 31.5 kHz; ranges of measured sound pressure levels at workstands in the 10–80 kHz frequency range. *Notes.* $L_{f,\ max}$—maximum sound pressure levels in the 1/3-octave band, $L_{f,\ eq,\ 8\text{-hr}}$—equivalent-continuous sound pressure levels in the 1/3-octave band normalized to a nominal 8-hr working day, MAI—values of maximum admissible intensity for ultrasonic noise [9].

levels normalized to a nominal 8-hr working day ($L_{EX,\ 8\text{-hr}}$) were determined from the collected frequency spectra, A-weighting corrections and effective times of exposure to ultrasonic noise. The resultant noise levels ranged from 67.1 to 113.1 dB, with the median value of 82 dB (Figure 3). The $L_{EX,\ 8\text{-hr}}$ levels exceeding MAI for audible noise (85 dB) were observed in 47.8% of cases; this mainly applied to welders with a nominal operating frequency of 20 kHz.

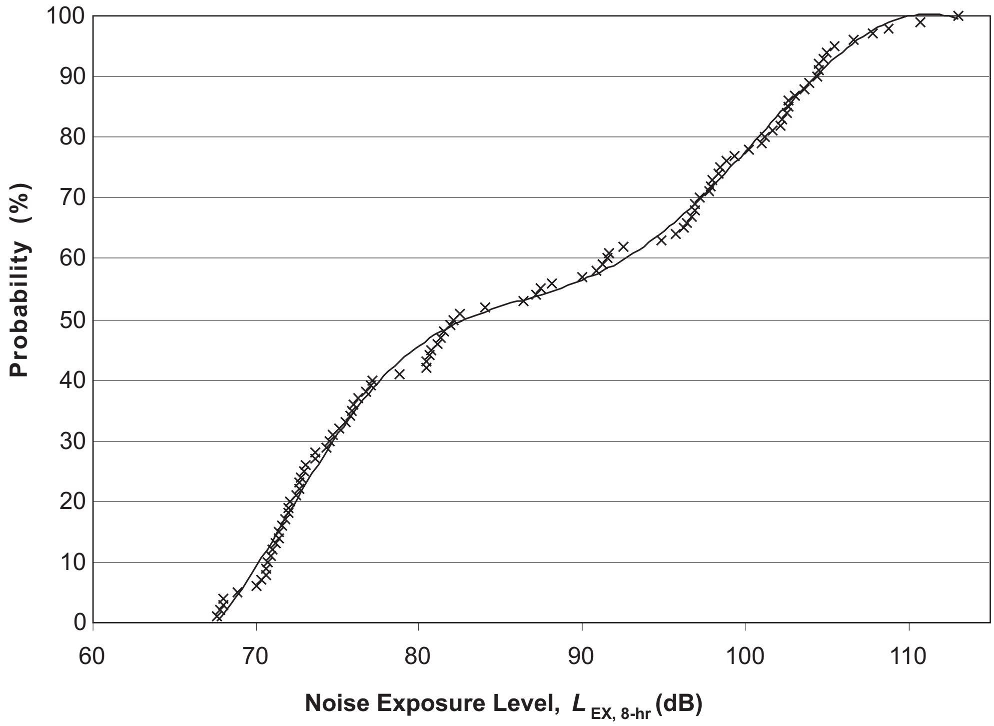

Figure 3. Distribution of calculated noise exposure levels normalized to a nominal 8-hr working day ($L_{EX, 8\text{-}hr}$) at workstands of operators of ultrasonic welders.

3.2. Questionnaire Inquires

Most subjects (83.3%) noticed noise at their workstands. However only 26.3% of them assessed the noise as more than *rather loud* and 17.6% as more than *rather annoying*, which corresponded to over 50 points on the 100–point scale. On the other hand, noise was evaluated as *loud* or *annoying* (over 75 points) by about 5% of workers. Median loudness and annoyance ratings were 45 and 30, respectively.

For 15% of workers this was their first place of employment; 30% reported noise at previous workplaces. Moreover, that noise was assessed as *very loud* by one third of subjects. Equally often it was described as *loud* or *not loud*.

Almost one third (29.4%) of workers did not subjectively report any ailments related to noise at their workstand. Some of them complained of fatigue (36.8%), headache (12.1%), drowsiness (5.3%), dizziness (5.3%) and palpitation (5.3%). The noise was described by workers as loud (52.6%), unsteady (44.4%), shrill (44.4%), annoying (36.8%), irritating (36.8%) and disturbing work (16.7%). However, most examined persons (64.7%) perceived noise as bearable. On the other hand, 26.3% of operators claimed that noise disturbed their conversations (26.3%), listening to the radio (21.1%) and prevented concentration (5.6%).

Generally, no workers reported essential hearing problems. Only a few of them complained of tinnitus (5.3%), difficulties with speech intelligibility in a noisy environment (10.5%) and not hearing whisper (10.5%).

3.3. Actual HTL

Results of workers' PTA are presented in Figure 4. The first examinations were performed up to 9.5 years after the date of employment (M = 2.8 years). On the other hand, intervals between tests varied from 0.8 to 7.4 years (M = 4 years).

Generally, the starting number (N = 19) of PTAs with normal hearing within the 1–8 kHz frequency range (HTL ≤ 20 dB HL) did not decrease after exposure to ultrasonic noise. Results of first and last hearing examinations did not differ significantly for the majority of

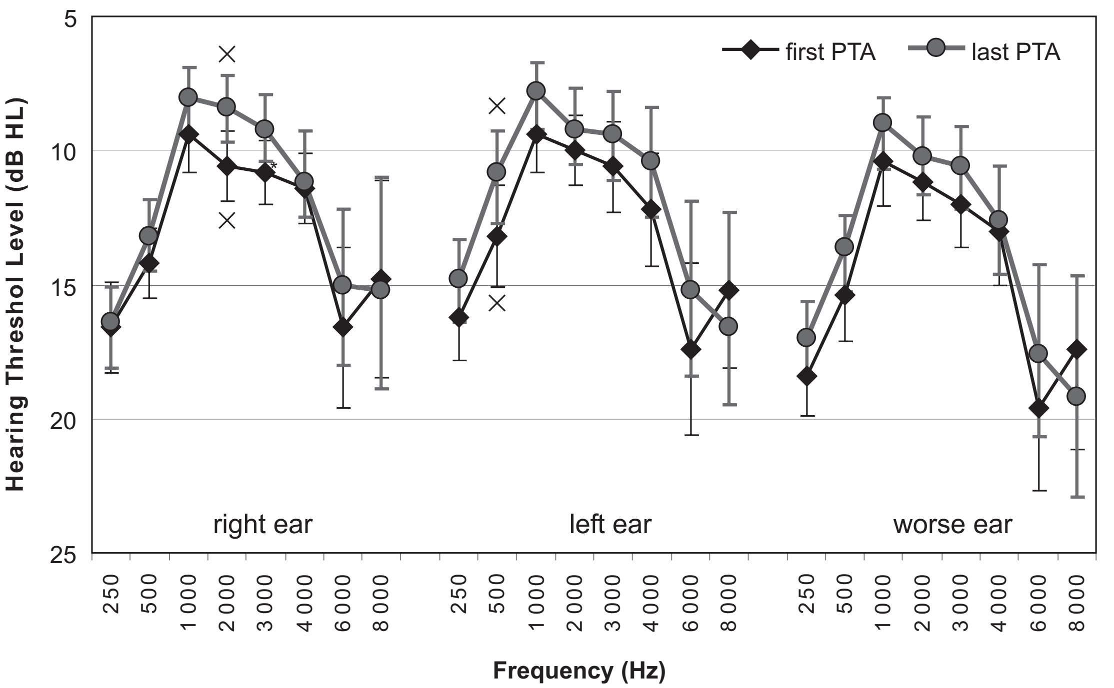

Figure 4. Results of first and last pure-tone audiometry (PTA) in workers exposed to ultrasonic noise (M ± 95% confidence levels). *Notes.* $^{\times}p < .05$.

the frequencies, with the exception of 500 and 2000 Hz for the left and right ear, respectively (Wilcoxon's matched pairs test, $p > .05$). Moreover, in the case of the worse ear, no significant differences between last and first PTAs were noted in the entire frequency range.

3.4. Predicted HTLs According to ISO 1999:1990 [12]

Results of the theoretical estimation of workers' HTLs are presented in Table 3 and in Figure 5. These predictions were based on noise exposure levels averaged over total tenure; they were calculated taking into account noise levels at the current workstand (values randomly selected from the distribution presented in Figure 3) and connected with previous job/jobs (estimated from questionnaire data).

No significant differences between actual and predicted median values of HTLs were found for the worse ear in the frequency range from 2000 to 6000 Hz (Mann–Whitney U test, $p > .05$). A similar relation was observed for the right ear, while the prediction obtained for the left ear did not differ significantly from the HTLs measured at 2000, 3000 and 6000 Hz.

Additionally, in order to compare predictions obtained for male and female workers of different age, and different duration and level of exposure to noise, standardized HTLs (SHTLs) were determined using the following formulas [14]:

$$SHTL = 1.282 \bullet (HTL - PHTL_{Q50}) / (PHTL_{Q10} - PHTL_{Q50}) \quad \text{for } HTL \geq PHTL_{Q50},$$

$$SHTL = 1.282 \bullet (HTL - PHTL_{Q50}) / (PHTL_{Q50} - PHTL_{Q90}) \quad \text{for } HTL < PHTL_{Q50},$$

where HTL is the actual HTL, in dB HL, $PHTL_{Q50}$ is the median value of predicted HTL, in dB HL, and $PHTL_{Q10/Q90}$ is the fractile Q10/Q90 of predicted HTL, in dB HL. The closer to the zero value of SHTL, the better the prediction of NIHL. On the other hand, positive values of SHTLs indicate that actual HTLs are higher than predicted.

Our results (Figure 6) confirmed the presented findings that the ISO 1999:1990 [12] method yielded fairly accurate predictions of noise-induced permanent threshold shift in the 2000–6000 Hz frequency range in operators of ultrasonic welders. It is very surprising because this international standard applies to noise at audio frequencies (lower than ~10 kHz).

TABLE 3. Actual and Predicted According to ISO 1999:1990 [12] Hearing Threshold Levels (HTLs) in Operators of Ultrasonic Welders (Range, $M \pm SD$)

		Frequency				
HTL (dB HL)		**1 000 Hz**	**2 000 Hz**	**3 000 Hz**	**4 000 Hz**	**6 000 Hz**
Actual	right ear	5–15	5–15	5–15	5–20	5–30
		8.0±2.9	8.4±3.1	9.2±3.4	11.2±4.8	15.0±7.1
	left ear	5–15	5–15	5–20	5–25	5–30
		7.8±2.9	9.2±3.7	9.4±4.2	10.4±5.0	15.2±8.5
	worse ear	5–15	5–15	5–20	5–25	5–30
		9.0±2.5	10.2±3.7	10.6±3.9	12.6±5.2	17.6±8.6
Predicted	fractile Q90	–5.7–(–0.3)	–8.7–(–0.6)	–5.7–2.4	–5.8–2.5	–8.3–3.0
		–2.8±1.6	–4.0±2.1	–2.6±2.1	–2.2±2.5	–3.3±3.1
	fractile Q50	0.5–7.1	1.8–15.9	4.9–17.4	5.9–20.7	4.8–22.0
		4.0±1.8	9.0±3.9	10.8±3.5	13.0±4.1	12.7±5.1
	fractile Q10	10.6–22.6	15.5–37.9	31.4–54.6	30.6–50.4	27.8–47.5
		17.2±3.4	28.9±5.8	43.5±6.7	42.2±6.0	38.5±6.3

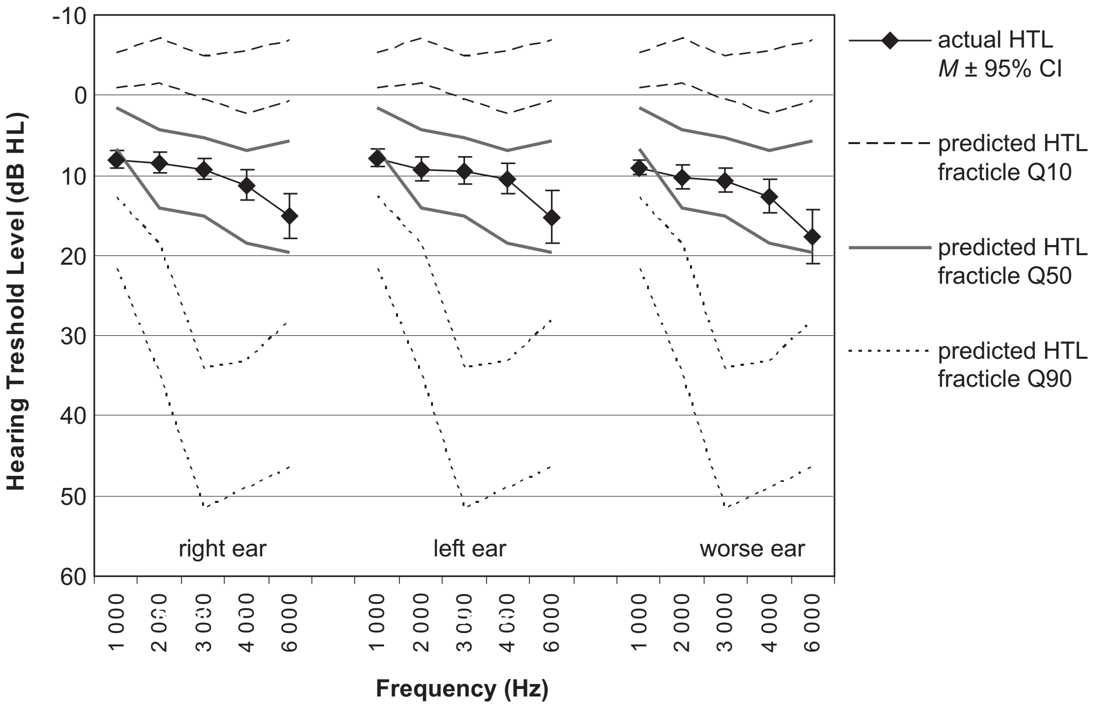

Figure 5. Workers' actual audiometric hearing threshold levels (HTLs) together with theoretical predictions calculated according to Standard No. ISO 1999:1990 [12]. *Notes.* Lines represent areas of fractile variations.

4. CONCLUSIONS

- Although overexposure to ultrasonic noise was observed in most operators of welders, no significant progress of hearing impairment was observed using PTA after exposure lasting up to 7 years.
- Since the introduction of exposure limits, there have not been much literature data showing permanent threshold shift resulting from occupational exposure to ultrasonic noise. Further studies on the hearing status of workers exposed to ultrasonic noise are needed.
- The ISO 1999:1990 [12] method for calculating noise-induced permanent threshold shift might also make quite reliable prediction possible after exposure to ultrasonic noise.

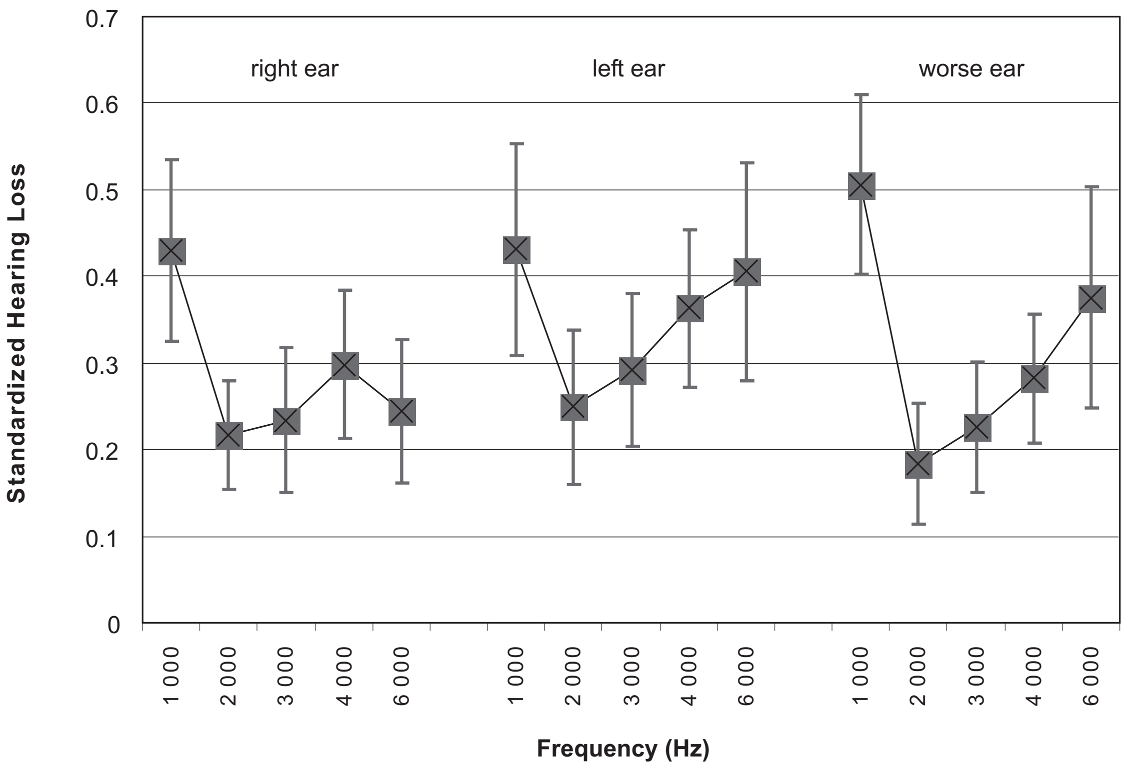

Figure 6. Standardized hearing threshold levels in operators of ultrasonic welders (*M* ± 95% CI).

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