

Analysis of temporary threshold shifts in hearing after exposure to ultrasonic noise

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Abstract This study presents preliminary results of evaluating the impact of ultrasonic noise on the auditory system, utilizing the most commonly employed method - pure-tone audiometry (PTA) for determining hearing thresholds. The research aimed to investigate the temporary threshold shifts (TTS) resulting from exposure to ultrasonic noise. Participants were exposed to ultrasonic noise within the frequency range of 16 kHz to 40 kHz, corresponding to the lower ultrasonic band typically emitted by industrial devices. The temporary threshold shift measurements, however, were conducted within the audible frequency range. Hearing thresholds were measured before and after exposure, within the standard range of 1 to 8 kHz and the extended range of 9 to 16 kHz. Twenty participants were exposed to two types of ultrasonic signals representing typical industrial sources - an ultrasonic cleaner and an ultrasonic welder. The analysis of results revealed statistically significant differences in hearing thresholds (both sides) for 8 kHz and 16 kHz after exposure to ultrasonic noise, regardless of the type of ultrasonic noise source. The average differences were 3.8 dB for 8 kHz and 5.8 dB for 16 kHz in the case of the ultrasonic cleaner, and 2 dB for 8 kHz and 3.5 dB for 16 kHz in the case of the ultrasonic welder. Despite smaller differences before and after exposure with the ultrasonic welder, the analysis did not show statistically significant differences regarding the influence of the type of noise source.

Keywords: ultrasound, workplace, noise measurement.

1. Introduction

The analysis of the results of acoustic field measurements in the workspaces of machines and devices used in the industry has shown that the main sources of ultrasonic noise posing the greatest threat to workers' health in the work environment are so-called low-frequency ultrasonic technological devices. In these devices, ultrasonic vibrations are generated for the purpose of implementing or accelerating or improving the planned technological processes. They are characterized by relatively large powers, and their nominal working frequency most often falls within the range of 18 ÷ 40 kHz [1].

Ultrasonic cleaners (washers) have found the widest application. They are made of special stainless and acid-resistant steel and are equipped with ultrasonic transducers that stimulate the cleaning liquid to vibrate, causing cavitation. Ultrasonic welders have also found widespread application. They are mainly used for welding metals, wire bundles, plastics, and materials that are non-weldable or difficult to weld using traditional methods. The operation of welders is based on generating a significant amount of heat at the point or line of the joint by a head called a sonotrode. The sonotrode induces vibrations of the materials being joined, generating heat due to the friction of the welded surfaces at a high frequency.

The dominant values of the sound pressure level for these devices usually occur in the frequency range from 20 kHz. The highest sound pressure level value generally occurs in the band with the middle frequency closest to the nominal working frequency of the device [2].

Based on numerous studies conducted both domestically and abroad, it has been shown that airborne ultrasound can penetrate the body through the auditory organ and the entire surface of the body, despite the lack of specific receptors on the skin, similar to electromagnetic or ionizing radiation [3, 4]. Consequently, in the impact of ultrasonic noise on humans, one can distinguish the impact on the auditory organ and other, so-called non-auditory effects.

Studies on the impact of ultrasonic noise on the condition of the auditory organ are difficult because, in industrial conditions, ultrasonic noise is usually accompanied by audible noise, and it is difficult to determine whether the changes in the hearing of the subjects occur as a result of the impact of only audible components or only ultrasonic components, or due to the simultaneous action of both components.

Lawton, in his 2001 report summarizing the results of studies and reports dating back to the 1960s, states that high-frequency and ultrasonic sounds are less dangerous to hearing than sounds in the frequency range below 8-10 kHz [3]. Meanwhile, recently published research results [5] indicate that the hearing condition of workers exposed to ultrasonic noise (ultrasonic welders) and audible noise is worse than the hearing condition of workers exposed only to audible noise at a similar A-weighted sound pressure level. Despite no significant differences in hearing up to 3 kHz, operators of ultrasonic devices have worse hearing in the 4-14 kHz range compared to the control group [6]. A change in hearing thresholds was noted in the high-frequency range (9-14 kHz) among individuals exposed to ultrasonic noise. Other study investigated the effects of age, occupational ultrasound, and noise exposure on hearing thresholds in both the conventional (0.125–8 kHz) and extended high-frequency range (9–18 kHz) [7]. Results showed that hearing sensitivity decreases with age, and workers exposed to ultrasonic noise had significantly elevated thresholds between 10 and 14 kHz, even after short-term exposure. Age was the main predictor of hearing loss, followed by exposure to ultrasound and noise, confirming the usefulness of high-frequency audiometry for early detection of hearing impairment in exposed workers. In contrast, a controlled pilot at 40 kHz with short, high-level exposure (~120 dB SPL, 5 min) found no immediate TTS on standard PTA, underscoring the need for refined protocols (including EHF testing) and better exposure metrics before firm risk limits can be set [8].

It is increasingly believed that due to nonlinear phenomena occurring in the ear itself, under the influence of ultrasonic action, subharmonic components are generated at sound pressure levels often almost the same order as the fundamental ultrasonic component. As a result of this phenomenon, hearing losses occur precisely for the frequencies of ultrasonic subharmonics. The latest systematic review and meta-analysis [9] investigated whether noise exposure affects extended high-frequency (EHF, 9–20 kHz) hearing in individuals with clinically normal audiograms. Drawing on 30 studies (~2,500 participants), the authors found that occupational noise exposure was significantly associated with elevated thresholds across 9–16 kHz, while recreational noise showed weaker and less consistent effects. The analysis indicates that EHF threshold elevation may serve as an early marker of subclinical cochlear damage, preceding detectable changes in the standard audiometric range (≤ 8 kHz).

During the operation of some ultrasonic devices (e.g., during ultrasonic welding), the generated noise has an impulsive character, which can also have a significant impact on the auditory organ [10]. Moreover, recent scientific reports also indicate significant discrepancies regarding the measuring equipment used in previous studies, which adversely affects the ability to compare the results obtained by different researchers. The results of a studies showed that differences in measurement results depending on the measuring equipment configuration can range from 2 to 5 dB for the 20-40 kHz range [11-13].

Therefore, there is a need to analyze existing scientific reports and conduct necessary laboratory and industrial research, including environmental interviews, to revise the permissible values of ultrasonic noise in the work environment and IRPA guidelines [14].

2.Methods

In pilot studies, the most commonly used method for assessing the hearing threshold - pure tone audiometry (PTA) - was used. For PTA studies, an Interacoustics AD629 diagnostic audiometer and Sennheiser HDA 200 audiometric headphones were used [15]. The aim of the studies was to assess temporary threshold shifts (TTS) as a result of exposure to ultrasonic noise. Hearing thresholds were determined twice - before exposure and after exposure. Threshold levels were determined in a limited standard range from 1 to 8 kHz and in an extended range from 9 to 16 kHz. The bracketing method was used according to ISO 8253-1:2010. Hearing thresholds were determined with a 1 dB step, bilaterally, starting each time from the right ear. The research station consisted of an area for exposure to ultrasonic noise and an audiometric testing chamber (see Fig. 1).

The large statistical population (about 50,000 workers at positions involving the operation of ultrasonic devices) made it impossible to use random selection methods that rely on a known and specified probability for each unit to be included in the sample during the pilot study. Instead, a non-random selection method was used, which involved pre-determining certain characteristics (including age, gender, hearing thresholds) that the individuals in the sample should meet – the structure was formed arbitrarily. The laboratory study involved 20 participants - 10 women and 10 men aged between 23 and 38.

Only individuals who met specific criteria, such as having no significant hearing loss and no chronic ear diseases, head injuries, or taking medications that could affect hearing, were allowed to participate in the study.



Figure 1. Study conducted in an audiometric chamber.

Two types of ultrasonic signals representative of sources found in the industry were prepared at the research station. A Sonic-0,5IS ultrasonic cleaner and a Branson Wire Splicer GMX-W1 ultrasonic welder were used for the tests.

The sources of ultrasonic noise were recorded in real industrial conditions using an RME Babyface PRO FS audio interface and a DPA 4007 microphone with a sampling rate of 192 kHz. They were then reproduced in laboratory conditions using Scan Speak Revelator R2904/700009 speakers and a Lab Gruppen LAB300 laboratory amplifier (stereo output power 4 Ω , 160 W per channel; bridged mono 4 Ω , 400 W). The acoustic source used in the experimental setup was a high-performance ring-dome tweeter. It is characterized by a nominal impedance of 4 Ω (with a minimum impedance of approximately 3.7 Ω) and a sensitivity of 94.5 dB measured at 2.83 V/1 m. The fundamental resonance frequency (F_s) of the transducer is 520 Hz, and the recommended operating frequency range extends from 2.5 kHz to 30 kHz, ensuring stable performance across the upper audible and low ultrasonic spectrum. The continuous power handling capacity of the tweeter is 160 W, which provides sufficient output for controlled laboratory simulations of high-frequency acoustic exposure. Due to previous research findings, a decision was made to filter out the audible components of the noise spectrum to assess the impact of ultrasonic components only. Due to the strong directivity of the speakers in the ultrasonic range, they were positioned using laser levels and controlled with a sound level meter (see Fig. 2). The sound level meter microphone was positioned in accordance with PN-Z-01339:2020, at a distance of approximately 10 cm from the entrance to the ear canal.



Figure 2. Positioning the speakers using laser levels.

The Figures 3 and 4 show the sound pressure levels at the research station, and the Figure 5 presents the time history of the sound pressure levels at the research station. The Figure 5 presents a selected fragment

of the time history to illustrate the temporal characteristics of the ultrasonic signals. At the test station, the ultrasonic signals were played in a 120-second loop. The use of looped signals enabled better control of the sound pressure levels throughout the duration of the experiment.

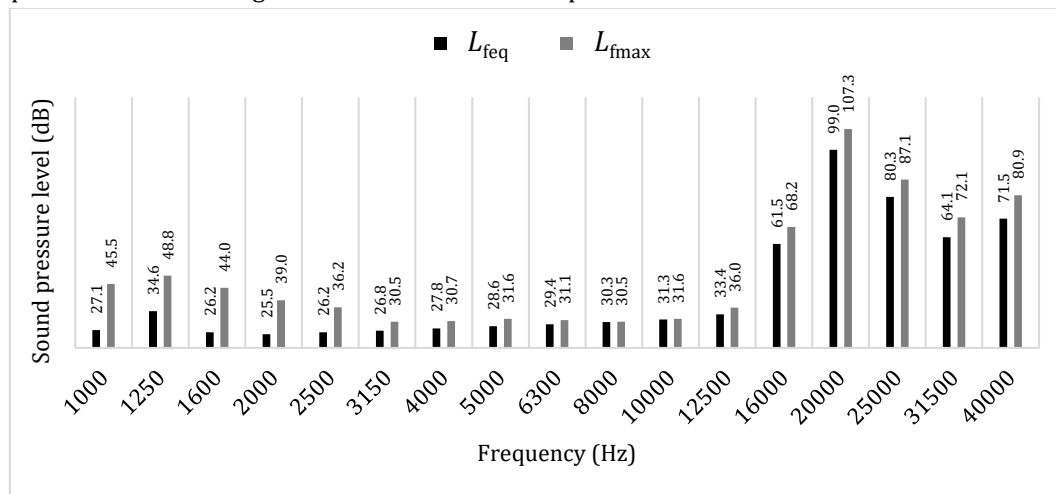


Figure 3. Sound pressure levels at the research station during exposure to ultrasonic noise from the ultrasonic welder (L_{feq} – equivalent sound pressure level and L_{fmax} – maximum sound pressure level).

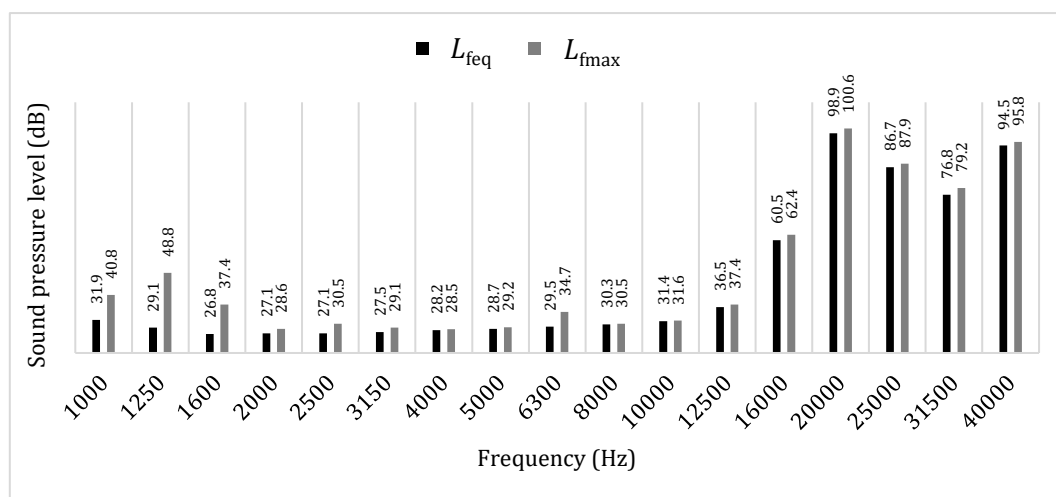


Figure 4. Sound pressure levels at the research station during exposure to ultrasonic noise from the ultrasonic cleaner.

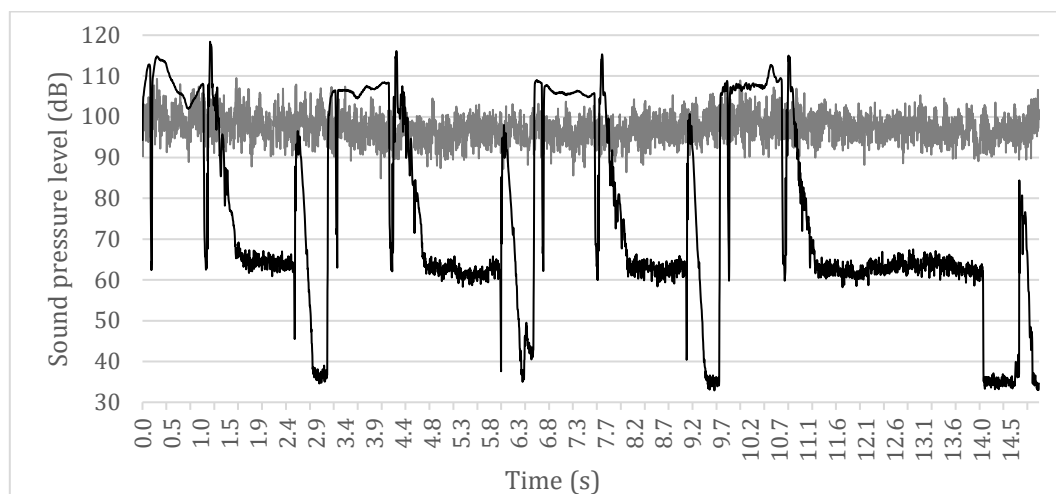


Figure 5. Selected segment of the time history of ultrasonic signals applied at the research station (grey line – ultrasonic cleaner, black line – ultrasonic welder).

The exposure time and sound pressure level were selected to not exceed the permissible exposure values related to an 8-hour daily work time [16] – the exposure time during the study was 1 hour.

Participants were divided randomly into two equal groups of 10. The first group was subjected to a one-hour exposure to ultrasonic noise from the ultrasonic cleaner. The second group was subjected to a one-hour exposure to impulsive ultrasonic noise from the ultrasonic welder.

3. Results

The differences in hearing threshold ΔHL before and after exposure to ultrasound from the ultrasonic cleaner are presented in the Figures 6 and 7.

The differences in hearing threshold ΔHL before and after exposure to ultrasound from the ultrasonic welder are shown in the Figures 8 and 9.

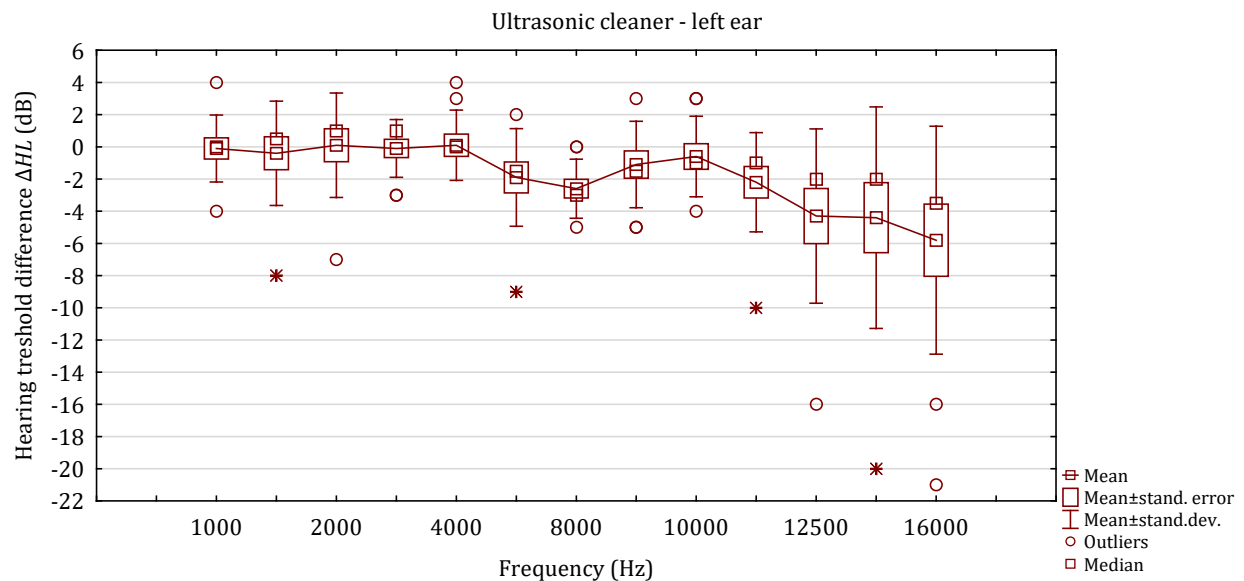


Figure 6. Difference in hearing threshold ΔHL before and after exposure to ultrasound from the ultrasonic cleaner (left ear).

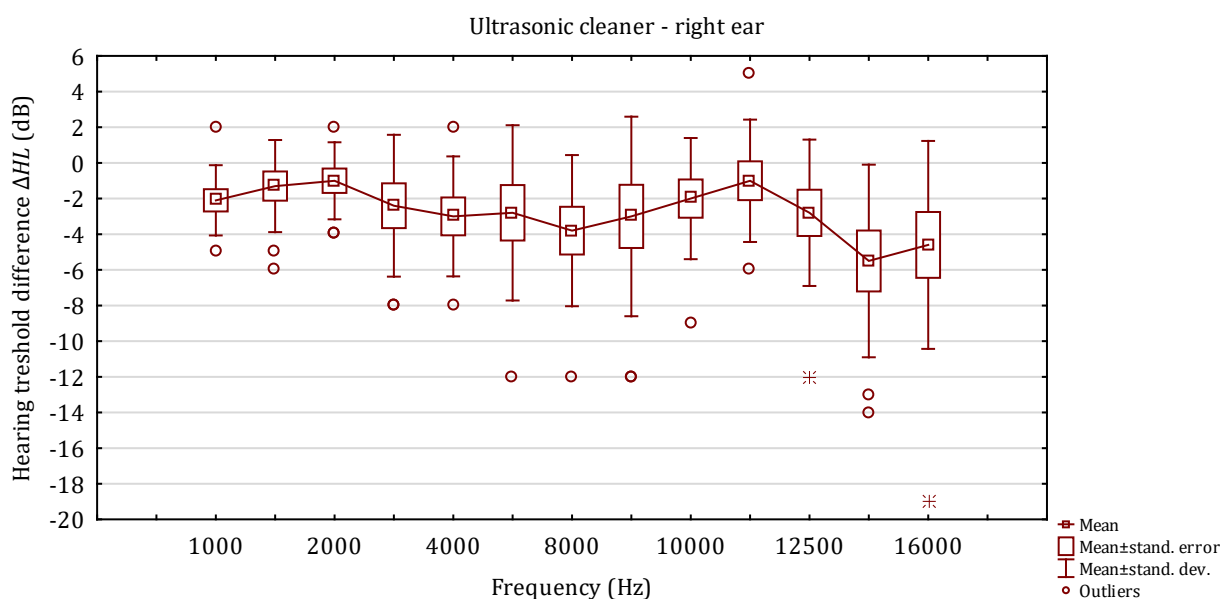


Figure 7. Difference in hearing threshold ΔHL before and after exposure to ultrasound from the ultrasonic cleaner (right ear).

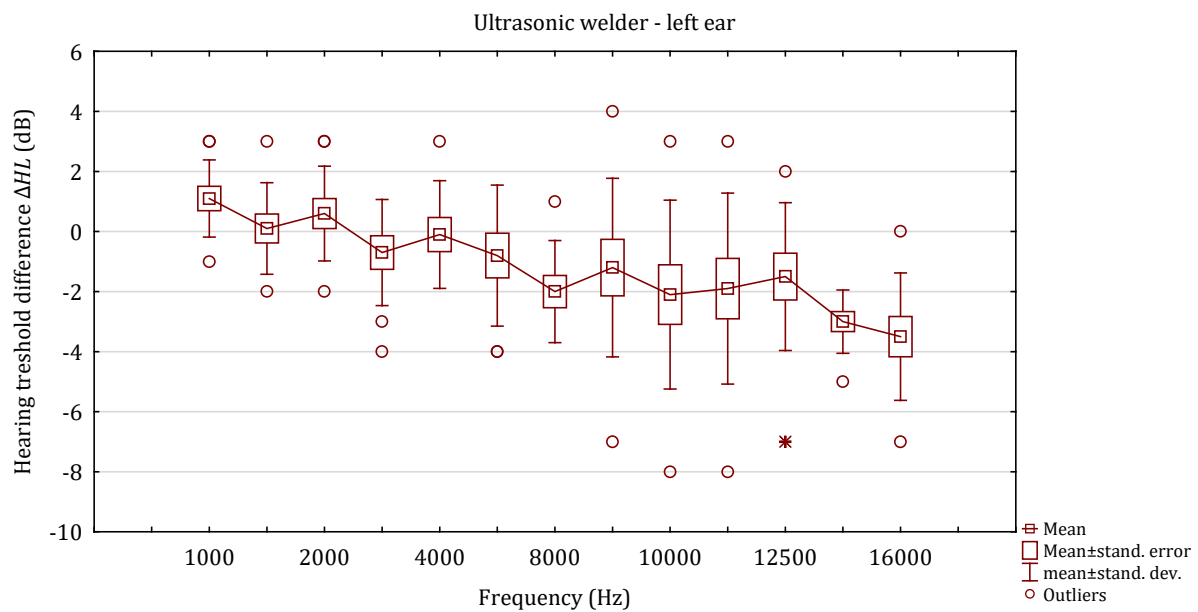


Figure 8. Difference in hearing threshold ΔHL before and after exposure to ultrasound from the ultrasonic welder (left ear).

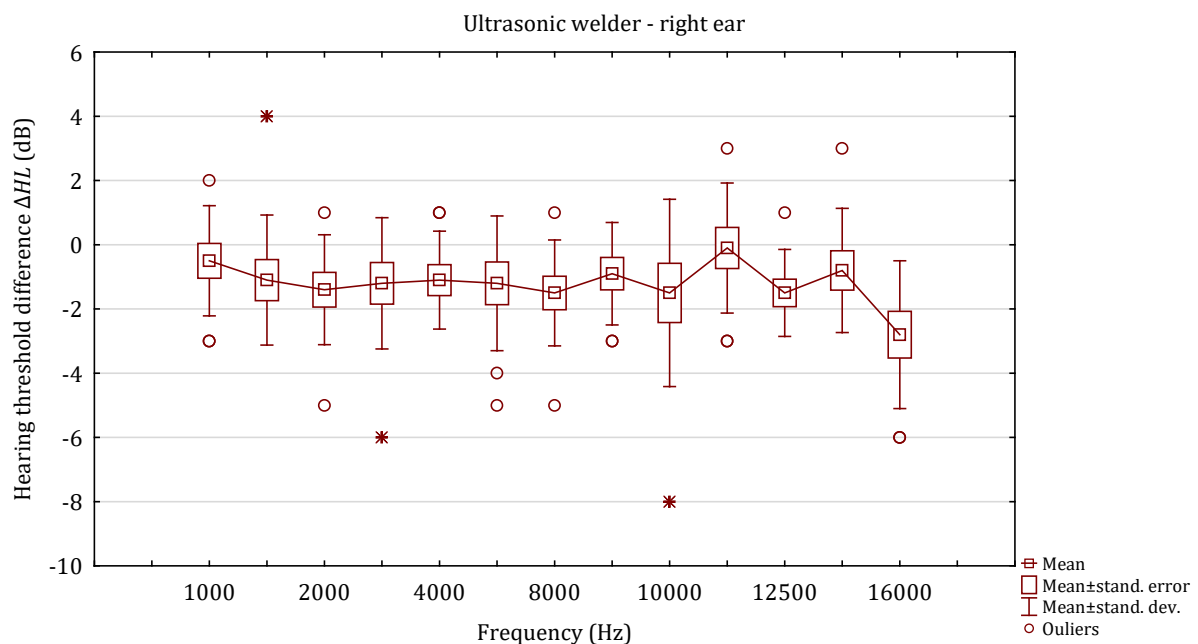


Figure 9. Difference in hearing threshold ΔHL before and after exposure to ultrasound from the ultrasonic welder (right ear).

Statistical analysis of dependent groups focuses on studying changes within one group as a result of introducing certain conditions, while analysis of independent groups compares two separate groups in terms of specific characteristics or variables. A key aspect of this process is also determining the level of statistical significance, which allows deciding whether the observed differences between groups are due to actual differences or merely result from random fluctuations. For comparing the impact of ultrasonic exposure (audiometric tests before and after exposure), tests for dependent groups were used (Student's t-test or Wilcoxon test, see Tables 1 – 4). For comparing the impact of exposure from different sources of ultrasonic noise, tests for independent groups were used (see Tables 5 and 6). Statistically significant differences ($p < 0.05$) are marked bold.

Table 1. Normality test of variable distribution and statistical significance of differences regarding the effect of exposure to noise from the ultrasonic cleaner for the left ear.

Ultrasonic cleaner – left ear													
f [Hz]	1000	1500	2000	3000	4000	6000	8000	9000	10000	11200	12500	14000	16000
Normality test (Shapiro-Wilk)													
p HL before	0.27	0.70	0.93	0.71	0.15	0.53	0.11	0.017	0.005	0.039	0.15	0.78	0.28
p HL after	0.67	0.39	0.52	0.90	0.35	0.77	0.19	0.040	0.002	0.005	0.78	0.80	0.006
Test of statistical significance of differences													
p	0.88	0.70	0.92	0.86	0.88	0.08	0.001	0.22	0.46	0.05	0.033	0.07	0.029

Table 2. Normality test of variable distribution and statistical significance of differences regarding the impact of exposure to noise from the ultrasonic cleaner for the right ear.

Ultrasonic cleaner – right ear													
f [Hz]	1000	1500	2000	3000	4000	6000	8000	9000	10000	11200	12500	14000	16000
Normality test (Shapiro-Wilk)													
p HL before	0.47	0.92	0.14	0.61	0.30	0.30	0.002	0.47	0.94	0.27	0.15	0.71	0.13
p HL after	0.05	0.87	0.40	0.99	0.27	0.27	0.015	0.36	0.58	0.06	0.25	0.92	0.26
Test of statistical significance of differences													
p	0.008	0.14	0.17	0.08	0.020	0.10	0.19	0.12	0.09	0.38	0.059	0.010	0.034

Table 3. Normality test of variable distribution and statistical significance of differences regarding the impact of exposure to noise from the ultrasonic welder for the left ear.

Ultrasonic welder – left ear													
f [Hz]	1000	1500	2000	3000	4000	6000	8000	9000	10000	11200	12500	14000	16000
Normality test (Shapiro-Wilk)													
p HL before	0.15	0.61	0.79	0.87	0.30	0.71	0.93	0.77	0.33	0.36	0.25	0.37	0.63
p HL after	0.10	0.97	0.32	0.67	0.83	0.91	0.17	0.99	0.72	0.025	0.018	0.38	0.53
Test of statistical significance of differences													
p	0.024	0.84	0.25	0.24	0.86	0.30	0.047	0.23	0.06	0.09	0.08	0.001	0.001

Table 4. Normality test of variable distribution and statistical significance of differences regarding the impact of exposure to noise from the ultrasonic welder for the right ear.

Ultrasonic welder – right ear													
f [Hz]	1000	1500	2000	3000	4000	6000	8000	9000	10000	11200	12500	14000	16000
Normality test (Shapiro-Wilk)													
p HL before	0.47	0.92	0.14	0.61	0.30	0.30	0.002	0.47	0.94	0.27	0.15	0.71	0.13
p HL after	0.05	0.87	0.40	0.99	0.27	0.27	0.015	0.36	0.58	0.06	0.25	0.92	0.26
Test of statistical significance of differences													
p	0.38	0.11	0.029	0.09	0.048	0.10	0.018	0.10	0.13	0.87	0.007	0.22	0.004

Table 5. Normality test of variable distribution and statistical significance of differences regarding the type of ultrasonic noise source for the left ear.

Type of noise source – left ear													
f [Hz]	1000	1500	2000	3000	4000	6000	8000	9000	10000	11200	12500	14000	16000
Normality test (Shapiro-Wilk)													
p Δ HL cleaner	0.42	0.07	0.023	0.023	0.09	0.14	0.11	0.58	0.15	0.000	0.05	0.015	0.009
p Δ HL welder	0.39	0.44	0.44	0.11	0.05	0.22	0.38	0.73	0.73	0.89	0.34	0.07	0.87
Test of statistical significance of differences													
p	0.13	0.66	0.66	0.46	0.82	0.37	0.45	0.93	0.25	0.83	0.15	0.53	0.33

Table 6. Normality test of variable distribution and statistical significance of differences regarding the type of ultrasonic noise source for the right ear.

		Type of noise source – right ear												
f [Hz]		1000	1500	2000	3000	4000	6000	8000	9000	10000	11200	12500	14000	16000
		Normality test (Shapiro-Wilk)												
p	ΔHL cleaner	0.36	0.041	0.39	0.11	0.70	0.12	0.09	0.14	0.23	0.78	0.20	0.046	0.044
	ΔHL welder	0.40	0.001	0.55	0.024	0.19	0.23	0.42	0.15	0.24	0.43	0.28	0.24	0.18
		Test of statistical significance of differences												
p		0.06	0.84	0.65	0.40	0.12	0.35	0.12	0.26	0.72	0.48	0.35	0.018	0.37

The analysis of the study results showed that as a result of ultrasonic noise exposure, there are statistically significant differences in hearing thresholds (bilaterally) for 8 kHz and 16 kHz. The average differences reached 3.8 dB for 8 kHz and 5.8 dB for 16 kHz in the case of the ultrasonic cleaner and 2 dB for 8 kHz and 3.5 dB for 16 kHz in the case of the ultrasonic welder. Although the differences in hearing thresholds (bilaterally) before and after exposure were smaller in the case of the ultrasonic welder, the analysis of the study results did not show statistically significant differences.

4. Discussion

These findings align with larger epidemiological datasets for workers operating low-frequency ultrasonic devices show significantly worse EHF thresholds ($\approx 10\text{--}14$ kHz) than matched controls exposed only to audible noise at similar A-weighted levels, with group differences also supported by OAE deficits, suggesting early cochlear involvement even when conventional PTA up to 3 kHz appears normal [5-7]. These patterns echo earlier observations that ultrasound-exposed populations exhibit elevated high-frequency thresholds relative to non-exposed groups, with age as the dominant predictor and ultrasound/noise exposures as secondary contributors. Taken together, the present TTS at 8–16 kHz provides short-term, within-subject evidence that complements population-level permanent changes, reinforcing the value of EHF audiometry (and OAEs) as outcome measures for ultrasonic-noise risk assessment [6]. Historically, it was argued that airborne ultrasound would not elicit auditory effects unless audible components were present [17]. However, more recent syntheses and this study indicate that down-conversion/nonlinear processes in the ear can reproduce risk at high audible frequencies even when the external audible spectrum is minimized [7]. The ICNIRP review of the legacy IRPA limits likewise concludes that while the endpoints (auditory effects, non-specific symptoms) remain health-relevant, the evidence base supporting specific band-limit values, especially around and above 20 kHz, has been limited and requires updating with improved dosimetry and outcome metrics [18]. From an exposure perspective, the pattern that was observed is plausible given that many industrial sources (ultrasonic welders, cleaners, textile machines) frequently exceed national admissible levels in the 10–25 kHz bands during routine operations, with exceedance rates exceeding 50% for several device categories in field surveys [1]. Limitations include the small sample, short follow-up, and reliance on PTA. Nevertheless, the direction and frequency-specificity of TTS match the cross-sectional EHF/OAE deficits documented in workplace cohorts, strengthening causal inference. Future work should combine EHF PTA with DPOAE/TEOAE to detect subclinical changes.

5. Conclusions

The pilot study attempted to estimate the impact of ultrasonic noise on the auditory organ, for which the most commonly used method for assessing hearing threshold - pure tone audiometry (PTA) - was utilized. Studies on the impact of ultrasonic noise on the condition of the auditory organ in industrial conditions are difficult because ultrasonic noise is usually accompanied by audible noise, and it is challenging to determine whether the changes in hearing occur as a result of the impact of audible components, ultrasonic components, or due to the simultaneous action of both components.

In the conducted studies, the "audible" part of the noise spectra from the cleaner and welder was filtered out. The analysis of the study results showed that as a result of ultrasonic exposure, there are statistically significant differences in hearing thresholds (bilaterally) for 8 kHz and 16 kHz, regardless of the type of ultrasonic noise source. The obtained results do not confirm the research carried out in the 60s [19], which indicated the absence of TTS as a result of ultrasonic exposure. However, they do confirm the results of research conducted by the Nofer Institute of Occupational Medicine [6], which indicate that the hearing condition of workers exposed to ultrasonic noise from ultrasonic welders is worse than the hearing condition of workers exposed only to audible noise at a similar A-weighted sound pressure level. The obtained results may confirm the occurrence of nonlinear phenomena in the ear itself, under the influence

of ultrasonic action, resulting in the generation of subharmonic components at sound pressure levels often almost the same order as the fundamental ultrasonic component. As a result of this phenomenon, there are shifts in hearing thresholds in the range of "audible" frequencies. Future studies could explore the long-term effects of such exposure, the reversibility of hearing threshold shifts, and the potential cumulative impact of repeated ultrasonic noise exposure.

The findings highlight the need for revised safety standards and health regulations in industrial environments where ultrasonic devices are prevalent. Current guidelines may need to be updated to incorporate protective measures against ultrasonic noise exposure, considering its proven effect on hearing thresholds.

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Additional information

The author declare: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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