ORIGINAL PAPER

International Journal of Occupational Medicine and Environmental Health 2022;35(3):309–325
https://doi.org/10.13075/ijomeh.1896.01816

HEARING STATUS OF PEOPLE OCCUPATIONALLY EXPOSED TO ULTRASONIC NOISE

ADAM DUDAREWICZ, MAŁGORZATA ZAMOJSKA-DANISZEWSKA, KAMIL ZABOROWSKI, and MAŁGORZATA PAWLACZYK-ŁUSZCZYŃSKA

Nofer Institute of Occupational Medicine, Łódź, Poland
Department of Physical Hazards

Abstract
Objectives: The aim of the study was to evaluate the hearing status of operators of low-frequency ultrasonic devices compared to employees exposed to audible noise at a similar A-weighted sound pressure level (SPL) but without ultrasonic components. **Material and Methods:** Standard pure-tone audiometry, extended high-frequency audiometry (EHFA), transient-evoked otoacoustic emissions (TEOAE), and distortion-product otoacoustic emissions (DPOAE), as well as questionnaire surveys were conducted among 148 subjects, aged 43.1±10.8 years, working as ultrasonic device operators for 18.7±10.6 years. Their exposure to noise within the ultrasonic and audible frequency range was also evaluated. The control group comprised 168 workers, adjusted according to gender, age (±2 years), tenure (±2 years), and the 8-hour daily noise exposure level ($L_{EX,8h}$) of ±2 dB. **Results:** The ultrasonic device operators and the control group were exposed to audible noise at $L_{EX,8h}$ of 80.8±3.9 dB and 79.1±3.4, respectively. The Polish maximum admissible intensity (MAI) values for audible noise were exceeded in 16.8% of the ultrasonic device operators, while 91.2% of them were exposed to ultrasonic noise at SPL>MAI values. There were no significant differences between the groups in terms of the hearing threshold levels (HTLs) up to 3 kHz, while the ultrasonic device operators exhibited significantly higher (worse) HTLs, as compared to the control group, in the range of 4–14 kHz. The results of the DPOAE and TEOAE testing also indicated worse hearing among the ultrasonic device operators. However, the differences between the groups were more pronounced in the case of EHFA and DPOAEs. **Conclusions:** The outcomes of all hearing tests consistently indicated worse hearing among the ultrasonic device operators as compared to the control group. Both EHFA and DPOAE seem to be useful tools for recognizing early signs of hearing loss among ultrasonic device operators. Int J Occup Med Environ Health. 2022;35(3):309–25

Key words:
noise, pure-tone audiometry, otoacoustic emissions, noise-induced hearing loss, ultrasonic noise, extended high-frequency audiometry

INTRODUCTION

Noise exposure is commonly regarded as the main hazard of occupational hearing loss. However, at many workplaces, there is broadband noise containing high-frequency audible and low-frequency ultrasonic components (including one-third octave bands of 10–40 kHz), which is called ultrasonic noise [1].

Low-frequency ultrasonic technological devices such as welding machines, washers, drills, soldering tools and galvanizing pots may be quoted as the main sources of ultrasonic noise in the occupational setting. Other typical industrial applications of low-frequency ultrasound include emulsification, dispersion, and homogenization processes. Apart from industry, low-frequency ultrasound has also been used in medicine, commerce, military service and at home. For example, the most popular domestic products using ultrasound are pest repellents, remote control, burglar alarms, and automatic camera focusing [2,3].

Funding: this study was supported by the Ministry of Health (project No. 2016–2020 6/4/10/NPZ/FRPW/2018/312/515/a).
Received: December 18, 2020. Accepted: November 4, 2021.
Corresponding author: Adam Dudarewicz, Nofer Institute of Occupational Medicine, Department of Physical Hazards, św. Teresy 8, 91–348 Łódź, Poland (e-mail: Adam.Dudarewicz@imp.lodz.pl).

Ultrasonic devices used in technological processes (including washing, drilling, soldering emulsification, and mixing) generate ultrasound not only at the operating frequency, but also at its harmonics. Moreover, these processes are generally carried out using ultrasound at high intensities that cause cavitation which is responsible for additional emissions of high-level audible noise [2]. However, there are also a number of machines or processes unintentionally generating ultrasonic noise, such as compressors, pneumatic tools, high-speed machinery – for instance, planers, millers, grinders, circular saws, some textile machinery, as well as plasma-arc welding and air-acetylene welding processes [4,5].

The potential adverse effects of low-frequency ultrasound and very high-frequency sound have been investigated for over half a century. However, relatively fewer papers on ultrasound impact, as compared to audible noise, have been published so far [1].

According to the literature data, especially the results of early studies, low-frequency airborne ultrasound has been recognized to cause auditory as well as non-auditory effects, in particular subjective symptoms, including fatigue, nausea, headache, vomiting, pain, disturbance of coordination, dizziness, etc. Other non-auditory effects such as thermal effects are rather unlikely to occur at the sound pressure levels (SPLs) normally occurring in the occupational and non-occupational settings, since they are supposed to appear at SPLs above 140–150 dB [2,3].

Already in the 1960–1970s, it was shown that low-frequency ultrasound was able to cause auditory effects, including the temporary and permanent deterioration of hearing acuity. It was believed that any hazards of ultrasound which affect hearing were due to the audible components of high-frequency subharmonics which accompany ultrasound itself [2,3,6–8].

The most common method for assessing the hearing status of noise-exposed workers is standard pure-tone audiometry (PTA) which is usually performed at frequencies of 250–8000 Hz. However, the extended high-frequency audiometry (EHFA), evaluating hearing thresholds of >8000 Hz, has been recognized as a more sensitive tool for identification of early signs of noise-induced hearing loss (NIHL) [9,10]. Evaluating otoacoustic emissions (OAEs) is another method that could be applied to monitor early signs of NIHL in addition to PTA rather than instead of it [11].

To the best of the authors' knowledge, only few studies measured OAEs among subjects exposed to ultrasonic noise. For example, Chopra et al. [12] analyzed the pre- and post-exposure transient-evoked otoacoustic emissions (TEOAE) among dental clinicians working with ultrasonic scalers and noted reduced OAE values immediately after using these devices.

As regards EHFA, >30 years ago, Grzesik and Pluta [13] demonstrated higher (worse) hearing threshold levels (HTLs) in the frequency range of 10–20 kHz among ultrasonic device operators as compared to the control group (comprising non-noise-exposed otologically normal subjects). At the same time, they did not note significant differences within the standard PTA frequency range.

The same authors analyzed the progress of hearing loss among ultrasonic device operators after 3 years of exposure, and they found an additional permanent threshold shift (PTS) (over and above aging) of 1 dB/year in the extended high-frequency range of 14–17 kHz for workers with prolonged exposure. What is more, their further investigation among ultrasonic device operators showed that occupational exposure to high-frequency noise at SPLs in the one-third octave bands of 10–16 kHz >80 dB might cause a hearing loss in the frequency range of 10–16 kHz [13–15].

Later on, Pawlaczyk-Łuszczyńska et al. [16] studied the results of standard PTA performed within the framework of the obligatory preventive medical examination in operators of ultrasonic welders, and they did not find any significant progress of the hearing loss after up to 7.4 years of exposure to ultrasonic noise.

More recently, Macca et al. [17] assessed the hearing condition with standard PTA and EHFA in workers exposed to ultrasonic noise (N = 24), industrial noise-exposed workers (N = 113) as well as non-noise-exposed subjects (N = 148), and found that the ultrasonic device operators had significantly higher (worse) hearing thresholds than the non-exposed ones at extended high frequencies, mostly of 10–14 kHz. Furthermore, those differences were quite evident after 5 years of exposure. However, the general conclusion of that study was that age was the primary predictor, and noise and ultrasound exposure acted as secondary predictors of the hearing thresholds in the extended high frequency range.

Dudarewicz et al. [18] also observed worse HTLs within the extended high-frequency range among workers exposed to ultrasonic noise, but in comparison with workers exposed to audible noise (without ultrasonic components) at a similar A-weighted SPL.

On the other hand, in the above-cited study conducted among dental clinicians working with ultrasonic scalers, in addition to the post-exposure reduction of OAEs, a significant temporary threshold shift in the standard PTA was observed [12]. What is more, some dentists reported a mild ear pain or tinnitus. However, according to the results of other investigations, the harmful impact of ultrasonic scalers on hearing is not quite obvious [13,14].

In the light of the presented literature data, the adverse impact of ultrasonic noise on workers' hearing has not been fully documented yet. Thus, the overall objective of the study was to analyze the hearing ability among operators of low-frequency ultrasonic technological devices in relation to their exposure to noise. In particular, the authors attempted to:

– evaluate the hearing status of employees exposed to ultrasonic noise in comparison with the hearing status of workers exposed to audible noise at a similar A-weighted SPL but without ultrasonic components;
– compare audiometric hearing thresholds in the ultrasonic device operators to the age-related reference data from the highly screened and unscreened populations.

MATERIAL AND METHODS

Study groups

Hearing tests and questionnaire surveys were carried out among 148 ultrasonic device operators. Their exposure to noise within the ultrasonic and audible frequency range was also evaluated.

The control group comprised 168 workers non-exposed to ultrasonic noise but adjusted according to age, gender, tenure and exposure to audible noise to the study subjects. This group was selected from the database compiled by authors, containing the results of previous research on the hearing status among people occupationally exposed to noise.

The participation in the study was voluntary. Both groups were recruited by advertisement. Prior to hearing examinations, otoscopy was performed. Only the persons who met the inclusion criteria, i.e., a normal otoscopy picture and no history of chronic ear diseases, head injury or ototoxic drugs, were included into the study. The subjects confirmed in writing their consent to participate in the investigation and obtained some numerations.

The study design and methods were approved by the Ethics Committee of the Nofer Institute of Occupational Medicine in Łódź, Poland (decision No. 18/2018 of November 20, 2018).

Hearing examinations

In each participant, the hearing ability of the right and left ears was tested by means of standard PTA and EHFA, as well as by measuring the distortion-product otoacoustic emissions (DPOAEs) and TEOAEs.

Hearing threshold levels were determined for both standard frequencies of 0.125–8 kHz and extended frequencies of 9–16 kHz with 5 dB steps. The bracketing method as specified in PN-EN ISO 8253–1:2011 was used in the case of PTA [19]. A similar methodology was applied for EHFA. However, in the latter case, the initial familiarization was carried out using a tone of 11.2 kHz. The order of tones ranged 11.2–16 kHz, followed by the lower-frequency range, in the descending order (i.e., 11.2–9 kHz). Standard PTA was always determined first, followed by EHFA. In both cases, the right ear was tested first. The hearing examinations were conducted with the Videomed Smart Solution (Szczawno-Zdrój, Poland) clinical audiometer, model AUDIO 4002 with the Holmberg GmbH & Co. KG Electroacoustics (Berlin, Germany) headphones, type Holmco PD-81 for the PTA, and the Sennheiser Electronic GmbH & Co. KG (Wedemark, Germany) headphones, type HAD 200 for EHFA.

The Scout Otoacoustic Emission System v. 3.45.00 (Bio-Logic Systems Corp., Mundelein, IL, USA) was applied to record and analyze otoacoustic emissions. For TEOAE measurements, a standard click stimulus at a SPL of about 80 dB was generated. Each response was windowed 3.5–16.6 ms post-stimulus and band-pass filtered at 0–6000 Hz. The total number of stimuli was 260. The artifact rejection level was set at 20 mPa. The amplitude and reproducibility of the response, as well as the noise floor during the measurements of TEOAE and the corresponding signal-to-noise ratios (SNRs), were determined for the overall frequency range and for half octave bands with central frequencies of 1, 1.5, 2, 3 and 4 kHz.

For DPOAE testing, a stimulus in the form of a 2-tone was used with the fixed ratio of frequencies f_1 and f_2 ($f_1/f_2 = 1.22$), and the intensity levels L_1 and L_2 of 65 dB and 55 dB, respectively. The amplitudes of the registered signals were determined at the $f_{dp} = 2f_1–f_2$ frequencies as a function of f1 and f2 frequencies (ranging approx. 1.5–10 kHz in the one-fourth octave intervals) together with the noise floor and the corresponding SNR.

Hearing tests were performed in a noise-free interval at least 14 h after work. These were carried out by the same investigator in the quiet rooms located close to the participants' workplaces (where the A-weighted equivalent-continuous SPL of the background noise level did not exceed 35 dB).

Questionnaire surveys

All participants were asked to fill in a questionnaire, first of all to collect basic data concerning their:

- age and gender,
- education and/or profession,
- work history,
- current job details,
- usage of hearing protection devices,
- medical history (past middle-ear diseases, ear surgery, head trauma, etc.).

Hearing ability of the study subjects and the control group was assessed using the (modified) *Amsterdam Inventory for Auditory Disability and Handicap* ((m)AIADH) [20]. This inventory consists of 30 items and includes 5 basic disability factors dealing with a variety of everyday listening situations:

- *Distinction of Sounds* (subscale I),
- *Auditory Localization* (subscale II),
- *Intelligibility in Noise* (subscale III),
- *Intelligibility in Quiet* (subscale IV),
- *Detection of Sounds* (subscale V).

The respondents were asked to report how often they were able to hear effectively in a specific situation. The 4 answer categories were as follows: almost never, occasionally, frequently, and almost always. Responses to each question were coded on a scale of 0–3; the higher the score, the less significant the perceived hearing difficulties. The total score per subject was obtained by adding the scores for 28 questions. The maximum total score of the questionnaire was 84. Additionally, the answers for each subscale were summed up (the maximum score for subscale I was 24, and 15 for the other subscales) [20].

Noise exposure evaluation

To identify the workplaces with exposure to ultrasonic noise and/or audible noise, prior to hearing tests, the measurements of SPLs were carried out at 116 work posts in 16 factories where the so-called low-frequency ultrasonic technological devices were used. These included the measurements of:

– the equivalent-continuous A-weighted SPL,
– the maximum A-weighted SPL,
– the peak C-weighted SPL,
– the equivalent-continuous and maximum SPLs in the one-third octave frequency bands of 0.002–40 kHz.

The noise surveys within the ultrasonic frequency range were performed using the method described in the measurement procedure for ultrasonic noise [21], while in the audible frequency range, they were carried out according to PN-N-01307:1994 and PN-EN ISO 9612:201 [22,23]. The Svantek (Warsaw, Poland) type SVAN912AE sound analyzer (equipped with a GRAS 1/4" microphone type 40BF, and Svantek type SV01A preamplifier) as well as the Svantek type SVAN958 sound analyzer were used to measure ultrasonic noise and audible noise, respectively.

For each subject, the individual exposure to noise within both audible and ultrasonic frequency ranges was evaluated based on the results of the aforesaid noise measurements and questionnaire data concerning the subject's work history. Exposure to ultrasonic noise was characterized by the equivalent SPLs normalized to a nominal 8-hour working day in the one-third octave frequency bands of 10–40 kHz ($L_{feq,8h}$ in dB), expressed as the energy mean of ultrasonic noise exposures at different work posts where the subjects worked at the current workplace. On the other hand, the exposure to audible noise was characterized by the noise exposure level normalized to a nominal 8-hour working day, averaged over the whole period of exposure to noise ($\langle L_{EX,8h} \rangle$). To obtain a more accurate assessment of exposure to audible noise, the work stands without exposure to ultrasonic noise were also taken into account.

Additionally, the participants' exposures were described by a noise immission level (L_{IM}), i.e., a measure of the cumulative noise energy to which an individual was exposed over time, calculated using the following formula:

$$L_{IM} = \langle L_{EX,8h} \rangle + 10 \times \log_{10}(T) \qquad (1)$$

where:
$\langle L_{EX,8h} \rangle$ – the daily A-weighted noise exposure level averaged over the whole length of exposure,
L_{IM} – the noise immission level,
T – the length of exposure in years.

The latter measure was very useful, especially when selecting the control group.

Data analysis

The mean values of audiometric HTLs, as well as the mean values of TEOAE and DPOAE parameters (i.e., the amplitude of responses, SNRs and reproducibility, where applicable), were analyzed in the study subjects. Differences between the ultrasonic device operators and the control group in terms of the results of hearing tests and the (m)AIADH outcomes were evaluated using the t-test for independent samples or – if the preconditions of its use were not met – the Mann-Whitney U test was applied.

In addition, the audiometric HTLs in the workers exposed to ultrasonic noise were compared to those expected in the equivalent – due to age and gender – highly screened and unscreened non-noise-exposed reference populations according to ISO 1999:2013 [24] and ISO 7029:2017 [25], as well as specified by Jilek et al. [26].

The Statistica v. 9.1. was used for statistical analysis. All tests were conducted with the assumed significance level of $p < 0.05$.

RESULTS

Characteristics of the study groups

The study group included 148 ultrasonic device operators aged 43.1±10.8 years (M±SD). Among them, 37% were women, while 63% were men. They had worked on average for 18.7±10.6 years in factories, where mainly ultrasonic welding or washing are used in technological processes.

The control group comprised 168 subjects, mainly call center operators, exposed at their workplace to noise without ultrasonic components, matched according to gender, age (±2 years), tenure (±2 years), and the daily noise exposure level (±2 dB). Table 1 summarizes basic characteristics of both groups, including noise exposure data presented in more detail in the next chapter.

Noise exposure evaluations

The noise measurements involved 115 work posts in 16 factories. Generally, about 950 samples of ultrasonic noise and 630 samples of audible noise were collected, lasting in total approx. 50 h and 40 h, respectively. The results of the aforesaid measurements are presented in Tables 2 and 3. The Polish maximum admissible intensity (MAI) values for ultrasonic noise were exceeded at approx. 33% of the workplaces, while for the audible noise in 23% of cases.

In the next stage, hearing tests and questionnaire surveys were conducted in 8 industrial plants among 148 operators of ultrasonic devices employed at 93 workstations. The SPLs measured at these workplaces are presented in Figure 1.

The study subjects were exposed to ultrasonic noise at the $L_{feq,8h}$ and L_{fmax} levels exceeding MAI values in 72.3% or 80.9% of the cases, respectively, and 91.2% of the cases exceeding any of the MAI values. On the other hand, the MAI value for audible noise in the occupational settings ($L_{EX,8h}$ = 85 dB) was exceeded in 16.8% of cases [27].

Generally, the ultrasonic device operators were exposed to audible noise at relatively low levels, with the value of the daily noise exposure level ($L_{EX,8h}$) M±SD 80.8±3.9 (Table 1). The mean noise levels in the control group were found slightly lower (by approx. 1 dB), but still significantly different from the noise levels for the ul-

Table 1. Characteristics of the study groups in the study on the hearing ability among operators of low-frequency ultrasonic technological devices in relation to their exposure to noise

Variable	Participants (N = 316)	
	control group (N = 168, 336 ears)	ultrasonic device operators (N = 148, 296 ears)
Males [%]	47.3*	37.2*
Age [years] (M±SD)	40.0±6.5	41.3±10.8
Tenure [years] (M±SD)	17.8±6.8	18.7±10.6
Noise exposure level normalized to a nominal 8-hour working day ($L_{EX,8h}$) [dB] (M±SD)	79.1±3.4*	80.4±4.3*
Total noise immission level (L_{IM}) [dB] (M±SD)	91.0±4.1*	92.1±5.3*

* Significant differences between the ultrasonic device operators and the control group ($p < 0.05$).

Table 2. Results of the audible noise measurements at 115 workplaces in 16 factories where ultrasonic devices were used in the study on the hearing ability among operators of low-frequency ultrasonic technological devices in relation to their exposure to noise

Statistics	Sound pressure level [dB]			
	A-weighted		C-weighted	
	max	equivalent-continuous	peak	equivalent-continuous
Min.	64.0	62.6	80.6	66.8
50th percentile	84.6	78.0	104.8	80.8
90th percentile	101.5	96.1	112.0	94.2
Max	107.3	104.0	117.9	102.0
Maximum admissible intensity values [27]	115.0	85.0*	135.0	–

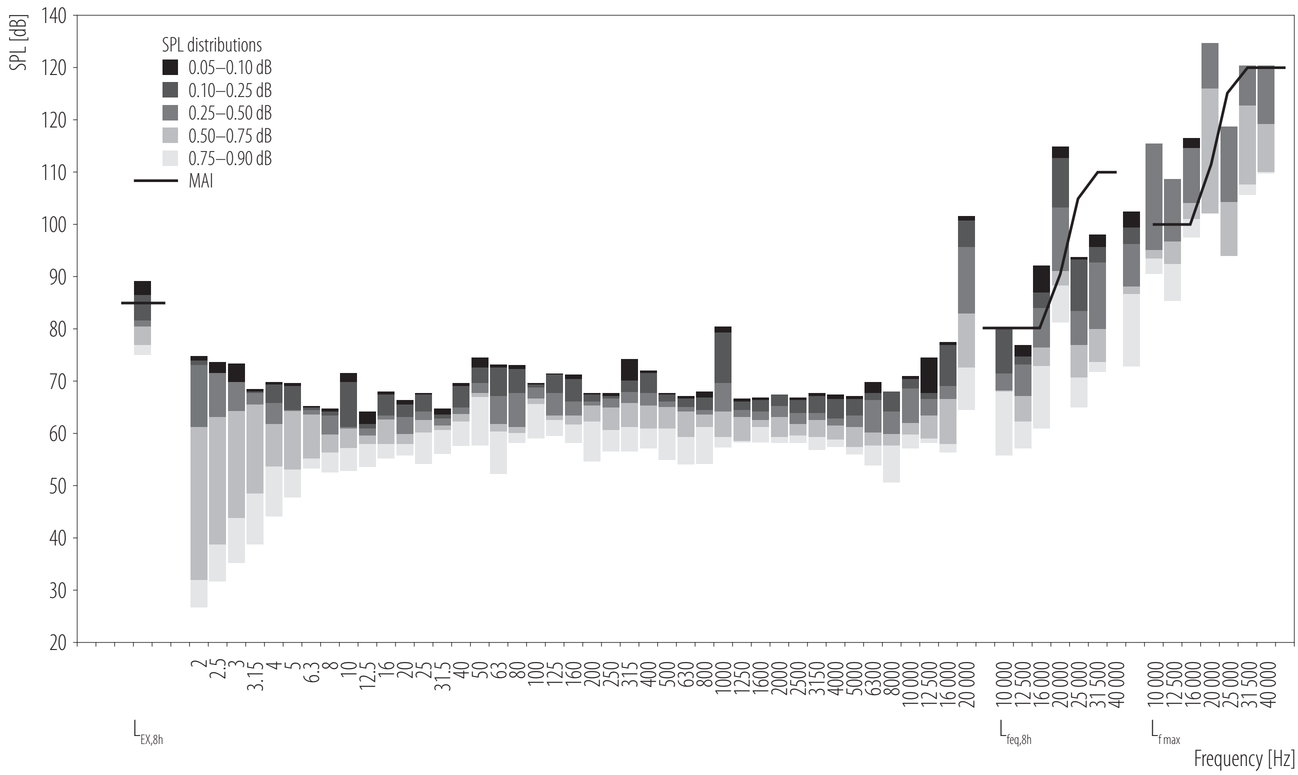
* Noise exposure level normalized to a nominal 8-hour working day.

Table 3. Results of the ultrasonic noise measurements at 115 workplaces in 16 factories where low-frequency ultrasonic devices were used in the study on the hearing ability among operators of low-frequency ultrasonic technological devices in relation to their exposure to noise

Device/machine	$L_{feq,8h}/L_{f\,max}$ [dB]						
	10 kHz	12.5 kHz	16 kHz	20 kHz	25 kHz	31.5 kHz	40 kHz
Ultrasonic cutter (f_o = 20 kHz) (Me)	54.5/68.4	55.6/68.7	74.1/87.0	93.2/106.4	75.5/89.0	57.7/70.6	70.9/84.7
Ultrasonic textile welding machine (f_o = 20 kHz) (Me)	67.1/77.7	74.7/82.9	93.4/101.5	110.5/120.5	91.9/102.9	78.7/88.5	94.9/104.9
Ultrasonic washer (Me)							
f_o = 20 kHz	53.6/61.0	51.1/57.8	69.9/76.4	76.1/83.7	55.0/61.6	48.4/55.2	53.5/58.1
f_o = 31.5 kHz	55.4/67.4	63.0/70.3	70.4/83.3	64.2/77.4	68.4/78.8	89.0/99.7	72.8/87.4
f_o = 40 kHz	49.3/63.8	50.5/65.2	57.8/72.1	67.6/81.1	56.1/70.3	67.7/83.1	86.2/101.6
Animal scarer (Me)							
f_o = 16 kHz	32.7/39.0	60.4/69.7	67.8/72.5	57.9/61.7	32.3/41.8	31.7/41.4	32.2/42.9
f_o = 20 kHz	30.6/32.4	30.7/31.7	47.8/49.6	51.3/56.0	57.1/69.2	45.0/52.3	47.7/57.1
f_o = 25 kHz	30.8/52.7	38.0/58.9	45.6/70.3	62.8/87.5	81.1/106.3	61.3/86.6	45.2/70.1
Welding machine (Me)							
f_o = 20 kHz	65.4/75.9	64.5/74.9	77.0/88.4	94.6/106.6	72.9/89.0	67.3/84.0	78.3/95.4
f_o = 31.5 kHz	65.2/71.0	63.8/71.8	66.0/80.6	68.0/81.4	77.9/93.3	102.5/119.1	99.9/116.0
f_o = 40 kHz	63.5/74.5	63.2/73.1	64.7/74.2	78.7/87.4	64.2/80.6	79.9/97.4	100.3/118.8
Maximum admissible intensity values [27]	80/100	80/100	80/100	90/110	105/125	110/130	110/130

$L_{feq,8h}/L_{f\,max}$ – equivalent-continuous sound pressure level in the one-third octave frequency band normalized to a nominal 8-hour working day/maximum sound pressure levels in the one-third octave frequency band.

f_o – the one-third octave band including the operating frequency of an ultrasonic device/machine.



$L_{EX,8h}$ – A-weighted noise exposure level normalized to a nominal 8-hour working day; $L_{feq,8h}$ – equivalent-continuous sound pressure levels normalized to a nominal 8-hour working day in the one-third octave bands in the frequency range of 10-40 kHz; $L_{f\,max}$ – maximum sound pressure levels in the one-third octave bands in the frequency range of 10–40 kHz; SPL – sound pressure level.

Figure 1. Noise spectra within the audible and ultrasonic frequency range among 148 ultrasonic device operators – distributions (in percentiles) of the measured sound pressure levels together with Polish maximum admissible intensity (MAI) values for audible noise and ultrasonic noise in the occupational settings [27]

trasonic device operators. Similar relationships between the groups were observed in the case of noise immission levels (Table 1).

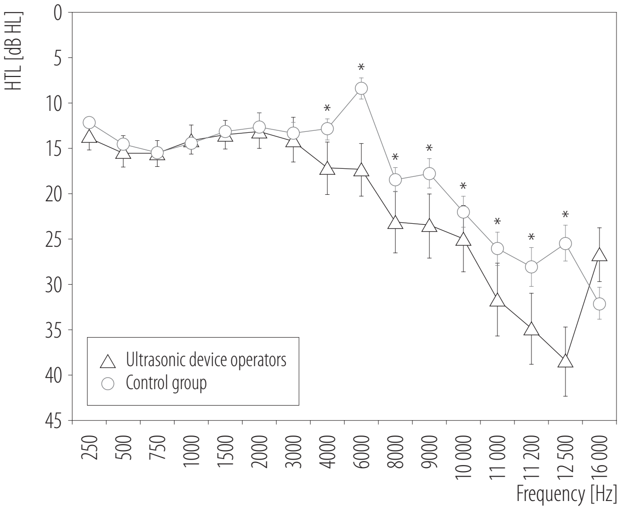
Hearing examinations

Audiometric tests

The results of PTA and EHFA in the group of ultrasonic device operators (296 ears) as well as in the control group (336 ears) are presented in Figures 2 and 3.

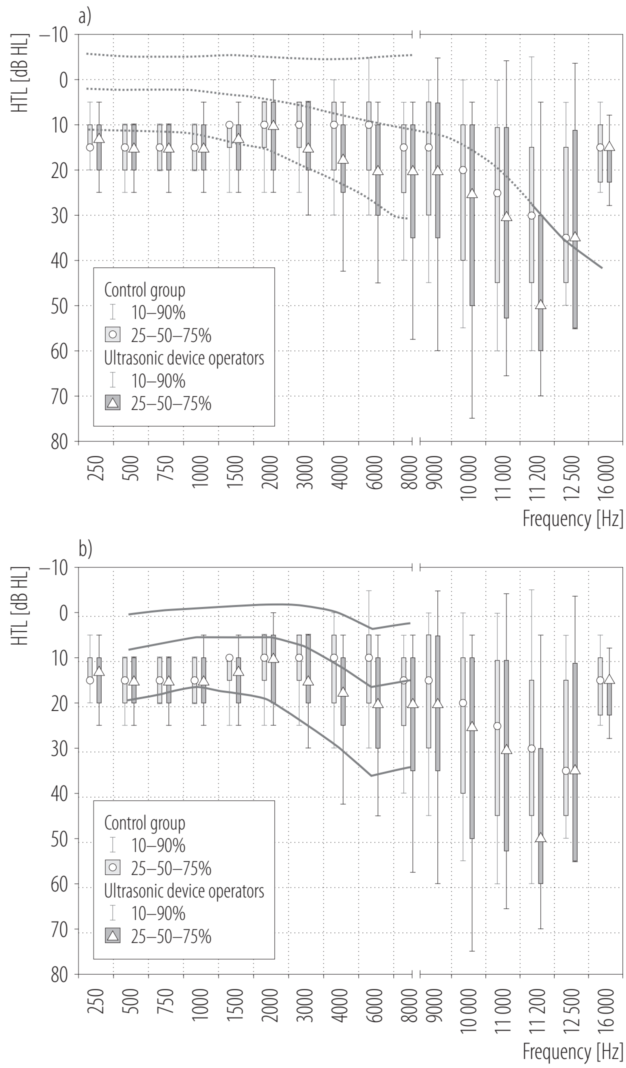
It is worth emphasizing that Figure 2 shows the mean values (with 95% confidence intervals) of the hearing thresholds in both groups, while Figure 3 presents the distributions of the actual HTLs in these groups, together with distributions of the expected hearing thresholds for equivalent – due to age and gender – highly screened and unscreened populations.

Reference data on the HTLs for the highly screened (otologically normal) population in the frequency ranges of 0.25–8 kHz and 9–12.5 kHz were calculated according to ISO 1999:2013 [24] and ISO 7029:2017 [25], respectively. In turn, the data on the HTLs of 0.5–8 kHz for the unscreened population were obtained from database B4, as specified in ISO 1999:2013 [24], while in the frequency range of 9–16 kHz, they were taken from Jilek et al. [26]. However, since the median values of the reference hearing thresholds at 9, 10, 11.2 and 12.5 kHz, calculated according



* Significant differences between the ultrasonic device operators and the control group ($p < 0.05$).
Data are given as mean values with 95% confidence intervals and concern both ears.

Figure 2. Audiometric hearing threshold (HTLs) levels determined in the ultrasonic device operators ($N = 148$) and the control group ($N = 168$), in the study on the hearing ability among operators of low-frequency ultrasonic technological devices in relation to their exposure to noise



Dotted and solid lines represent median values of the 10th, 50th and 90th percentiles of the hearing threshold levels in the reference populations.

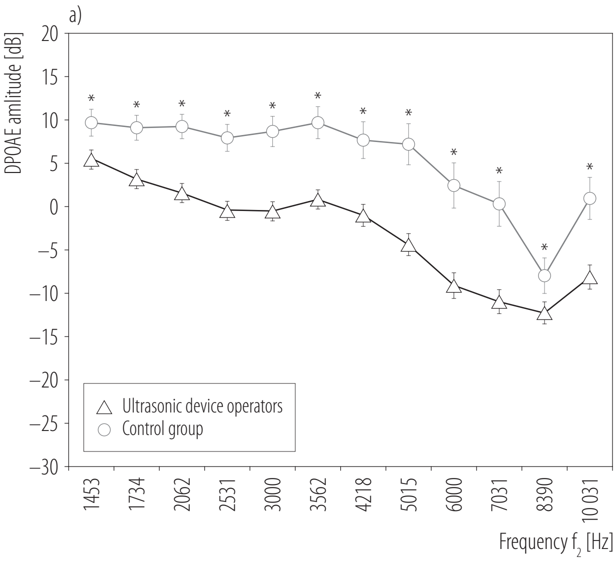
Figure 3. Statistical distributions of the hearing threshold levels (HTLs) in the ultrasonic device operators ($N = 148$) and the control group ($N = 168$), compared to HTLs in a) an equivalent due to age and gender, highly screened non-noise-exposed reference population according to ISO 1999:2013 (database A) [24] and ISO 7029:2017 [25] (dotted lines), and Jilek et al. [26] (solid line), b) unscreened reference populations according to ISO 1999:2013 (database B4) [24]

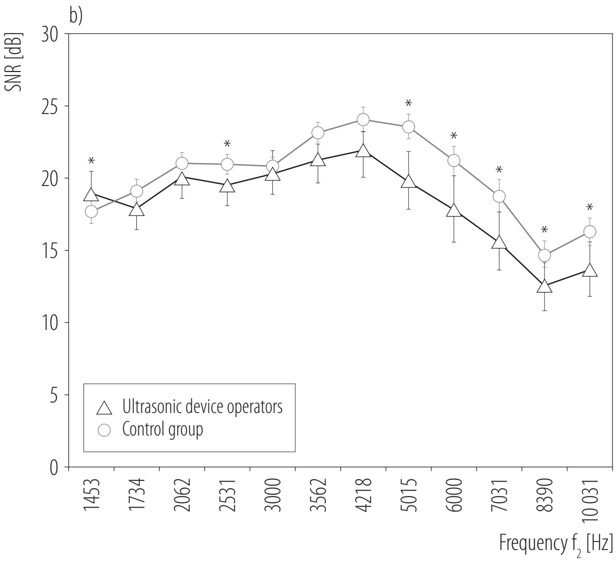
to Jilek et al. [26] and ISO 7029:2017 [25], are very similar, the latter data are not shown on the graph (Figure 3).

As can be seen in Figure 2, there were no significant differences between both groups in terms of the mean HTLs up to 3 kHz, while in the frequency range of 4–14 kHz, the ultrasonic device operators had higher (worse) HTLs than the control group ($p < 0.05$).

The median values of HTLs were comparable in both groups in the frequency ranges of 0.25–2 kHz and 14–16 kHz. In turn, the hearing thresholds were consistently higher among the study subjects as compared to the control group between 3–12.5 kHz (Figure 3). Moreover, some differences between the groups can be seen at >2 kHz in the shape of the hearing thresholds distributions. These differences are most pronounced within the extended high-frequency range and they confirm the tendency to worse hearing among workers exposed to ultrasonic noise as compared to the control group (Figure 3).

Basically, within the whole frequency range (excluding 4, 6 and 8 kHz in the case of the control group), in both groups the median values of the actual hearing thresholds were worse than in the highly screened (otologically





* Significant differences between the ultrasonic device operators and the control group ($p < 0.05$).
Data are given as mean values with 95% confidence intervals and concern both ears.

Figure 4. Distortion-product otoacoustic emissions (DPOAEs) measured in the ultrasonic device operators (N = 148) and the control group (N = 168), i.e., a) DPOAE amplitudes and b) signal-to-noise ratios (SNR), in the study on the hearing ability among operators of low-frequency ultrasonic technological devices in relation to their exposure to noise

normal) non-noise-exposed reference populations. In contrast, the HTLs among the workers exposed to ultrasonic sound were close to those expected in the unscreened reference population at 1.5, 2 and 14 kHz, while at other frequencies (excluding 16 kHz) they were higher (worse). As regards the control group, their median hearing thresholds were close to those expected for the reference unscreened population in the frequency range of 1.5–8 kHz, as well as at 12.5 and 14 k Hz, while at 6 kHz it was better (Figure 3).

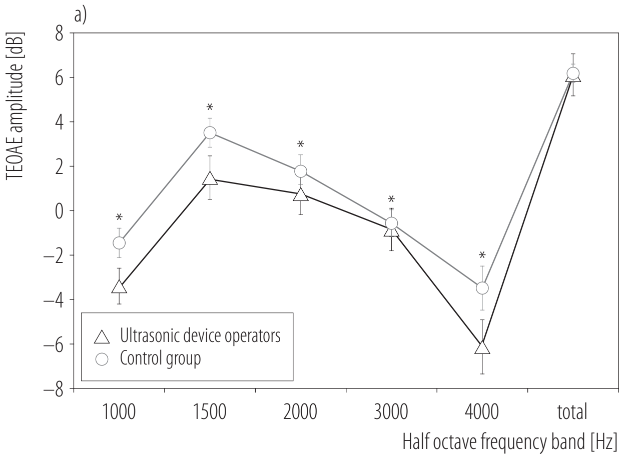
Otoacoustic emissions

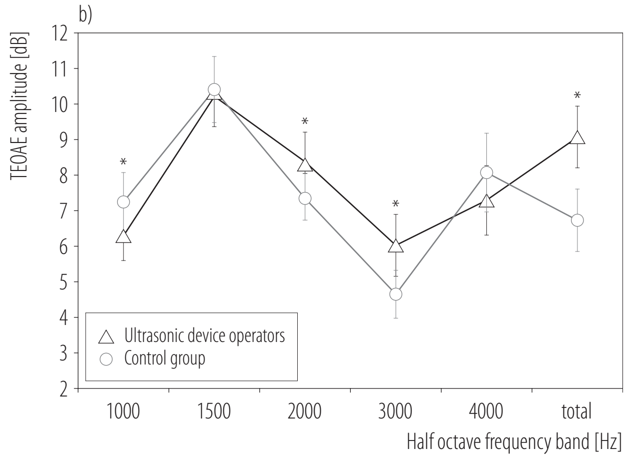
The results of the DPOAE and TEOAE testing in the group of ultrasonic device operators and in the control group are presented in Figures 4 and 5, respectively. There were some significant differences between the groups in terms of the OAE outcomes.

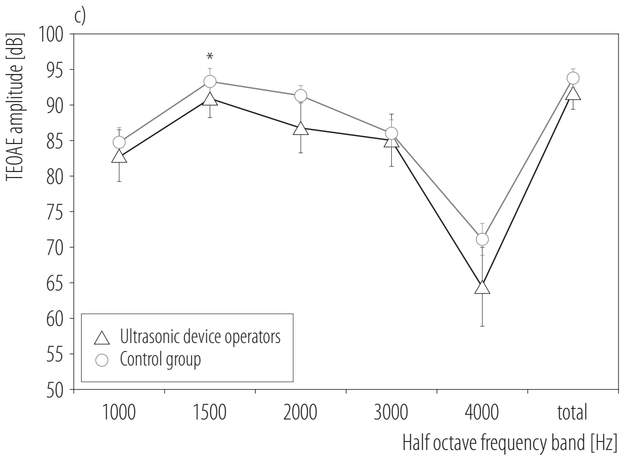
As regards the DPOAE measurements, the workers exposed to ultrasonic noise exhibited significantly reduced (worse) values of signal amplitude as compared to the control group in the whole analyzed frequency range (Figure 4a). Similar relations were observed in the case of the SNR values at higher frequencies ranging 5016–10 031 Hz, as well as at 2531 kHz, while at the lowest frequency of 1453 Hz, the ultrasonic device operators achieved significantly better results than the control group (Figure 4b).

As regards the TEOAE recordings, the mean values of the signal amplitude in the frequency bands of 1000, 1500, 2000 and 4000 Hz, as well as the reproducibility of responses in the frequency band of 1500, consistently indicated significantly worse hearing among the ultrasonic device operators than in the control group ($p < 0.05$) (Figure 5a). On the other hand, the SNR values in the case of total response and in the frequency bands of 2000 and 3000 indicated better hearing among the ultrasonic device operators, while a reverse relationship was noted for 1000 Hz.

In the case of the TEOAE recordings, the subjects exposed to ultrasonic noise proved to be significantly lower (worse), as compared to the control group, in the mean values of the signal amplitude in the frequency bands of 1000, 1500, 2000 and 4000 Hz. A similar tendency was visible when analyzing the reproducibility of TEOAEs.







* Significant differences between the ultrasonic device operators and the control group ($p < 0.05$).
Data are given as mean values with 95% confidence intervals and concern both ears.

Figure 5. Transient-evoked otoacoustic emissions (TEOAEs) measured in the ultrasonic device operators (N = 148) and the control group (N = 168), i.e., a) TEOAE amplitudes, b) signal-to-noise ratios (SNR), and c) reproducibility of responses, in the study on the hearing ability among operators of low-frequency ultrasonic technological devices in relation to their exposure to noise

However, the latter differences between the groups achieved statistical significance only in the frequency band of 1500 Hz. It also turned out that the ultrasonic device operators had lower (worse), as compared to the control group, mean values of the SNR only in the frequency band of 1000 Hz, while a reverse relationship was noted for 2000 and 3000 Hz, as well as for total response (Figure 5).

Questionnaire survey

The hearing ability self-assessment in terms of the score in the (m)AIADH in the group of ultrasonic device operators and the control group are presented in Table 4. Generally, workers exposed to ultrasonic noise obtained the mean total score equal to 81.5±14.7% of the maximum value (84), which suggests no substantial hearing problems (Table 4).

There were significant differences between the groups, both in the total score and in the scores of all subscales. Generally, the ultrasonic device operators reached lower, as compared to the control group, scores in the (m)AIADH, indicating, in particular, a poorer ability related to distinction of sounds, auditory localization, understanding speech in noise, intelligibility in quiet, and detection of sounds.

DISCUSSION

Already in the 1960–1970s, it was suggested that low-frequency ultrasound can cause auditory effects, including temporary and permanent hearing threshold shifts. How-

Table 4. Hearing ability in terms of the score in the (modified) Amsterdam Inventory for Auditory Disability and Handicap ([m]AIADH) in the ultrasonic device operators and the control group, in the study on the hearing ability among operators of low-frequency ultrasonic technological devices in relation to their exposure to noise

(m)AIADH	(m)AIADH score			
	control group (N = 168)		ultrasonic device operators (N = 148)	
	M±SD	10th/50th/90th percentile	M±SD	10th/ 50th/90th percentile
Total	70.3±7.9*	63/73/81	68.5±12.3*	51/71/82
Subscale				
I – *Distinction of Sounds*	21.0±2.1*	19/23/24	20.8±3.6*	15/22/24
II – *Auditory Localization*	12.5±1.7*	12/14/15	12.2±2.7*	9/12/15
III – *Intelligibility in Noise*	10.7±2.2*	10/12/14	10.6±3.0*	6/11/14
IV – *Intelligibility in Quiet*	12.9±1.8*	10/12/14	12.2±2.5*	6/11/14
V – *Detection of Sounds*	13.1±1.6*	10/14/15	12.8±2.3*	8/13/15

* Significant differences between the ultrasonic device operators and the control group ($p < 0.05$).

ever, since that time relatively fewer studies, as compared to "ordinary" noise, have been published on the negative impact of ultrasonic noise on the hearing acuity of workers [2,3,6–8]. Thus, the overall objective of this study was to analyze the hearing status among workers exposed to ultrasonic noise.

As mentioned in the beginning, for years the golden standard in the diagnosis of NIHL has been the standard PTA usually performed in the frequency range of 125 (250)–8000 Hz. However, since EHFA, DPOAE and TEOAE are believed to be useful for monitoring early signs of NIHL [9–11], thus, in the present study, being a continuation of the authors' previous investigations [18], the aforesaid hearing tests were applied together with the standard PTA for an assessment of hearing among ultrasonic device operators.

Industrial applications of low-frequency ultrasound include various uses which differ not only in terms of operating frequency, but also spectral and temporal characteristics of generated noise. This study comprised workers employed in factories where low-frequency ultrasound applications, such as welding and washing, were mainly used. In particular, ultrasonic welding devices were the most common ultrasonic devices in use, and in these workplaces the ultrasonic noise levels were the highest.

However, since industrial devices, including welding machines and washers, besides low-frequency ultrasound also generate audible noise, it is rather difficult to distinguish if the auditory effects occur due to the impact of only high-frequency audible or only ultrasonic components of noise, or as a result of simultaneous action of both these factors.

Thus, in order to analyze the impact of ultrasonic noise on the workers' hearing status, their exposure to noise within both ultrasonic and audible frequency ranges was evaluated at first. Secondly, the control group was tested, comprising subjects occupationally exposed to noise without ultrasonic components, matched according to gender, age, tenure, and the daily noise exposure level. Thirdly, the hearing status of workers exposed to ultrasonic noise was compared to the control group. In addition, the actual audiometric HTLs among ultrasonic device operators were compared to the age-related reference data from highly screened and unscreened populations.

It is worth underlining that ISO 1999:2013 [19] includes statistical distributions of HTLs in the highly screened (otologically normal) non-noise-exposed population (database A) as well as distributions of the HTLs compiled from unscreened populations of 3 typical industrialized societies (databases B2, B3 and B4). What is more, databases B2 and B3 represent the populations that have not been exposed to occupational noise, whereas participants with occupational noise exposure are included in database B4 [19]. In the present study, the reference data on HTLs for the highly screened population were obtained from database A and ISO 7029:2017, while for the unscreened population, they were taken from database B4 and from Jilek et al. [24–26]. It is worth noting that the latter authors determined reference HTLs in the extended high-frequency range of 9–16 kHz as a function of age [26].

As regards noise exposure evaluation, the ultrasonic noise was measured according to the method described in the measurement procedure which was first, in 2015, approved by the Polish Interdepartmental Commission for Maximum Admissible Concentrations and Intensities for Agents Harmful to Health in the Working Environment, and recently, it has been specified in the new Polish standard (PN-Z-01339:2020-12) [28]. In addition, the standard method specified by PN-EN ISO 9612:2011 and PN-N-01307:1994 was applied for an assessment of exposure to audible noise [19,22].

According to the obtained results of noise measurements, the Polish MAI values for ultrasonic noise were exceeded in approx. 74% of the study subjects [27]. Simultaneously, they were exposed to audible noise at relatively low levels with a mean value of daily noise exposure level ($L_{EX,8h}$) of 80.4±4.3 dB. Exposures exceeding MAI values for audible noise were noted in approx. 17% of the cases.

The control group had to be also exposed to audible noise at relatively low levels and, therefore, comprised mainly office workers, in particular call center operators. They were chosen from the database compiled in the Department of Physical Hazards of the Nofer Institute of Occupational Medicine in Łódź, which contains the results of previous research on the hearing status among people occupationally exposed to noise. Finally, the control group was exposed to audible noise at a mean daily noise exposure level of 79.1±3.4 dB, i.e., a slightly lower, but statistically significant, than the study subjects.

In this investigation, both the ultrasonic device operators and the control group were exposed to audible noise at relatively low levels (~80 dB), thus relatively low PTS were found up to 3 kHz in both groups. Furthermore, in this frequency range, the hearing thresholds in both groups were similar (Figure 2). What is more, at 4 and 6 kHz, the hearing thresholds in the control group were similar to those in the highly screened non-noise-exposed population according to ISO 1999:2013 [24] and ISO 7029:2017 [25] (Figure 3). A similar relationship was observed for 9 kHz and 12.5 kHz. This may be related to the fact that at high frequencies, age-related adverse auditory effects predominate over those induced by audible noise [17].

In this study, there were no significant differences between both groups in the mean hearing thresholds up to 3 kHz, whereas the ultrasonic device operators exhibited significantly higher (worse) HTLs, as compared to the control group, in the frequency range of 4–14 kHz. Furthermore, a systematic increase in the hearing threshold was observed in the extended high-frequency range of 9–14 kHz among workers exposed to ultrasonic noise (Figure 2).

In turn, a decrease in HTLs at 16 kHz, which was observed in both groups, is due to age and a limited range of testing signals generated by an audiometer. It is worth noting that the upper limit frequency of hearing decreases with age, and in about 40-year-old people it is approx. 15.5–16 kHz. Furthermore, it has been shown that only 10% of the 40-year-old population can hear sounds at frequencies >15 kHz [29].

The previously cited Ahmed et al. [9] and Somma et al. [10] suggested that hearing at the extended high frequencies might be more sensitive to noise, particularly in the case of younger subjects. Therefore, due to similar age and noise exposure (within audible frequencies) in both groups, and the presence of additional exposure to ultrasonic noise only in one of them, the latter factor might be the reason for the differences in HTLs observed in this study.

Generally, the obtained results of audiometric tests, in particular EHFA, indicating worse hearing in the ultrasonic device operators, as compared to the control group, confirm the outcomes from the earlier studies, especially those carried out by Grzesik and Pluta [13–15], and Macca et al. [17].

As mentioned in the beginning, the measurement of OAEs could also be used to monitor the early signs of NIHL. Generally, OAEs are weak acoustic signals generated in the inner ear and registered in the outer ear, whose measurement is used as an objective hearing test. They occur either in response to an acoustic stimulus or spontaneously [11]. However, it has not been established yet if DPOAEs and/or TEOAEs can be applied as diagnostic tools for subjects exposed to ultrasonic noise.

In the present study, the workers exposed to ultrasonic noise achieved significantly reduced (worse), as compared to the control group, mean values of the DPOAE amplitudes and SNRs. Moreover, the aforesaid differences, depending on the DPOAE parameter – the signal amplitude or SNR – were visible for all or the majority of the analyzed frequencies, respectively (Figure 4).

In the case of the TEOAE testing, likewise in the case of DPOAE measurements, the ultrasonic device operators exhibited reduced values of the signal amplitude in the whole analyzed frequency range, but excluding the total response. They also achieved significantly lower (worse), as compared to the control group, reproducibility in the frequency band of 1000 Hz. However, similar (or other clear) conclusions could not be drawn when analyzing SNRs.

Nevertheless, the results of all hearing tests consistently indicated worse hearing among the ultrasonic device operators as compared to the control group. Furthermore, the differences between the groups were more pronounced in the case of EHFA and DPOAEs, since they were visible for almost all (or the majority of) the analyzed frequencies and all analyzed variables. Thus, these 2 hearing tests seem to be useful tools for recognizing early signs of NIHL among workers exposed to ultrasonic noise.

It is worth noting that recently Mehrpavar et al. [30] analyzed 3 different tests for the early diagnosis of NIHL (i.e., the standard PTA, EHFA and DPOAE) among subjects exposed to noise, and concluded that EHFA was the most sensitive.

However, this study was not without limitations. As mentioned earlier, the control group was selected from the database containing the results of previous research on the hearing status among people occupationally exposed to noise. It was necessary to choose subjects whose hearing was evaluated using the same protocol as in the case of ultrasonic device operators. Such a condition reduced the number of available cases. Consequently, the control group consisted largely of call center operators whose data on noise exposure were limited to $L_{EX,8h}$.

Another limitation of the study was the assumption that the recent exposures reflect the life-long exposure in a similar manner. Furthermore, the ultrasonic device operators were about 1 year older and had a 1 year longer working experience, and were exposed to the daily noise exposure levels that were about 1 dB higher than for the control group. Although the only differences in noise levels achieved statistical significance, all the aforesaid differences might add-up to partly explain the differences in hearing between the groups. Therefore, a further study is needed before any firm conclusion concerning the risk of hearing impairment among subjects exposed to ultrasonic noise can be formulated.

CONCLUSIONS

Ultrasonic devices, such as welders and washers, generate broad-band noise, including both audible and low-frequency components. According to the results of this study, operators of the aforesaid devices were exposed to audible noise at A-weighted daily noise exposure levels ($L_{EX,8h}$) of 80.8±3.9 dB. The Polish maximum admissible intensity [27] values for audible noise was exceeded in 17% of the study workers, whereas approx. 74% of them were exposed to ultrasonic noise at SPLs higher than the MAI values established for this type of noise.

There were no significant differences in the HTLs up to 3 kHz between the ultrasonic device operators and the control group, comprising workers exposed to audible noise (without ultrasonic components) at similar $L_{EX,8h}$ and adjusted for age, gender and tenure. Simultaneously, the ultrasonic device operators exhibited significantly higher (worse) HTLs, as compared to the control group, in the range of 4–14 kHz. Furthermore, a systematic increase in the hearing threshold was observed in the extended high-frequency range of 9–14 kHz among workers exposed to ultrasonic noise.

Results of the DPOAE and TEOAE testing also indicated worse hearing among the ultrasonic device operators as compared to the control group. However, the differences between the groups were more pronounced in the case of EHFA and DPOAEs. Furthermore, given the similar age and exposure to noise in the audible frequency range in both groups, and the presence of additional exposure to ultrasonic noise only in one of them, it appears that ultrasonic noise may be the cause of the aforesaid differences in hearing ability.

To sum up, the findings presented in this paper confirm that ultrasonic device operators are at risk of hearing impairment; therefore, they should be included in the hearing conservation program. It also appears that further studies are needed, in particular based on the longitudinal design, comprising a greater number of workers of diversified exposure to ultrasonic noise as well as a longer duration of employment, before any firm conclusions concerning the risk of NIHL among ultrasonic device operators can be formulated. Meanwhile, EHFA as well as DPOAEs seem to be useful tools for recognizing early signs of NIHL among workers exposed to ultrasonic noise.

REFERENCES

1. Pawlaczyk-Łuszczyńska M, Dudarewicz A. Impact of very high-frequency sound and low-frequency ultrasound on people – A current state of art. Int J Occup Med Environ Health. 2020;33(4):389–408, https://doi.org/10.13075/ijomeh.1896.01586.
2. Environmental Health Criteria 22, Ultrasound. Published under the joint sponsorship of the United Nations Environment Programme, the World Health Organization, and the International Radiation Protection Association. Geneva: World Health Organization; 1982.
3. Health Canada. Guidelines for the Safe Use of Ultrasound: Part II – Industrial and Commercial Applications. Safetycode 24. Catalogue No. H46–2/90–158E [Internet]. Ottawa: Ministry of Supply and Services Canada; 1991 [cited 2019 Dec 13]. Available from: https://www.canada.ca/en/health-canada/services/environmental-workplace-health/reports-publications/radiation/guidelines-safe-use-ultrasound-part-industrial-commercial-applications-safety-code-24.html
4. Pawlaczyk-Łuszczyńska M, Dudarewicz A, Śliwińska-Kowalska M. [Sources of occupational exposure to ultrasonic noise-evaluation of selected devices]. Med Pr. 2007;58(2):105–16. Polish.
5. Smagowska B. Ultrasonic noise sources in a work environment. Arch Acoust. 2013;38(2):169–76, https://doi.org/10.248/aoa-2013-0919.
6. Acton WI, Carson MB. Auditory and subjective effects of airborne noise from industrial ultrasonic sources. Br J Ind Med. 1967;24(4):297–304, https://doi.org/10.1136/oem.24.4.297.
7. Parrack HO. Ultrasound and industrial medicine. Ind Med Surg. 1952;21(4):156–64.

8. Acton WI. The effects of industrial airborne ultrasound on humans. Ultrasonics. 1974;12(3):124–8, https://doi.org/10.1016/0041-624X(74)90069-9.
9. Ahmed HO, Dennis JH, Badran O, Isamil M, Ballal SG, Ashoor A, et al. High frequency (10–18 kHz) hearing thresholds: reliability, and effects of age and occupational noise exposure. Occup Med. 2001;51(4):245–58, https://doi.org/10.1093/occmed/51.4.245.
10. Somma G, Pietroiusti A, Magrini A, Coppetta L, Ancona C, Gardi S, et al. Extended high frequency audiometry and noise induced hearing loss in cement workers. Am J Ind Med. 2008;51(6):452–62, https://doi.org/10.1002/ajim.20580.
11. Helleman HW, Eising H, Limpens J, Dreschler WA. Otoacoustic emissions versus audiometry in monitoring hearing loss after long-term noise exposure – a systematic review. Scand J Work Environ Health. 2018;44(6):585–600, https://doi.org/10.5271/sjweh.3725.
12. Chopra A, Thomas BS, Mohan K, Sivaraman K. Auditory and nonauditory effects of ultrasonic scaler use and its role in the development of permanent hearing loss. Oral Health Prev Dent. 2016;14(6):493–500, https://doi.org/10.3290/j.ohpd.a36520.
13. Grzesik J, Pluta E. High-frequency hearing risk of operators of industrial ultrasonic devices. Int Arch Occup Environ Heath. 1983;53(1):77–88, https://doi.org/10.1007/bf00406179.
14. Grzesik J, Pluta E. High-frequency noise-induced hearing loss: a field study on the role of intensity level and accumulated noise dose. Int Arch Occup Environ Health. 1986;57(2):127–36, https://doi.org/10.1007/BF00381380.
15. Grzesik J, Pluta E. Dynamics of high frequency hearing loss of operators of industrial ultrasonic devices. Int Arch Occup Environ Health. 1986;57(2):137–42, https://doi.org/10.1007/bf00381381.
16. Pawlaczyk-Łuszczyńska M, Dudarewicz A, Sliwińska-Kowalska M. Theoretical predictions and actual hearing threshold levels in workers exposed to ultrasonic noise of impulsive character – a pilot study. Int J Occup Saf Ergon. 2007;13(4):409–18, https://doi.org/10.1080/10803548.2007.11105098.
17. Macca I, Scapellato ML, Carrieri M, Maso S, Trevisan A, Bartolucci GB. High-frequency hearing thresholds: effects of age, occupational ultrasound and noise exposure. Int Arch Occup Environ Health. 2015;88(2):197–211, https://doi.org/10.1007/s00420-014-0951-8.
18. Dudarewicz A, Zaborowski K, Rutkowska-Kaczmarek P, Zamojska-Daniszewska M, Śliwińska-Kowalska M, Zamysłowska-Szmytke E, et al. The hearing threshold of employees exposed to noise generated by the low-frequency ultrasonic welding devices. Arch Acoust. 2017;42(2):199–205, https://doi.org/10.1515/aoa-2017-0022.
19. PN-EN ISO 8253-1:2011 Acoustics – Audiometric test methods – Part 1: Pure-tone air and bone conduction audiometry. Warszawa: Polish Committee for Standardization; 2011.
20. Meijer AG, Wit HP, Tenvergert EM, Albers FW, Muller Kobold JE. Reliability and validity of the (modified) Amsterdam Inventory for Auditory Disability and Handicap. Int J Audiol. 2003;42(4):220–6, https://doi.org/10.3109/14992020309101317.
21. Radosz J. [Procedure for measuring ultrasonic noise]. Podstawy i Metody Oceny Środowiska Pracy. PIMOSP. 2015;4(86):169–90, https://doi.org/10.5604/1231868X.1192088. Polish.
22. PN-N-01307:1994. [Noise – Permissible values of noise in the workplace – Requirements relating to measurements]. Warszawa: Polish Committee for Standardization; 1994. Polish.
23. PN-EN ISO 9612:2011. [Acoustics – Determination of occupational noise exposure – Engineering method]. Warszawa: Polish Committee for Standardization; 2011. Polish.
24. ISO 1999:2013. Acoustics – Estimation of noise-induced hearing loss. Geneva: International Organization for Standardization; 2013.
25. ISO 7029:2017. Acoustics – Statistical distribution of hearing thresholds related to age and gender gender. Geneva: International Organization for Standardization; 2017.

26. Jilek M, Suta D, Syka J. Reference hearing thresholds in an extended frequency range as a function of age. J Acoustical Soc Am. 2013;136(4):1821–30.
27. [Regulation of the Minster of Family, Labour and Social Policy of 12 June 2018 on maximum admissible concentration and maximum admissible intensity values for agents harmful to human health in the work environment. J Law. item 1286]. Polish.
28. PN-Z-01339:2020-12 [Ultrasonic noise – Requirements for measurements in the work environment]. Warszawa: Polish Committee for Standardization; 2020. Polish.
29. Lawton BW. Damage to human hearing by airborne sound of very high frequency or ultrasonic frequency Contract Research Report No 343/2001 [Internet]. Institute of Sound and Vibration Research for the Health and Safety Executive; 2001 [cited 2020 Dec 20]. Available from: http://www.hse.gov.uk/research/crr_pdf/2001/crr01343.pdf.
30. Mehrparvar AH, Mirmohammadi SJ, Davari MH, Mostaghaci M, Mollasadeghi A, Bahaloo M, et al. Conventional Audiometry, Extended High-Frequency Audiometry, and DPOAE for Early Diagnosis of NIHL. Iran Red Cres Med J. 2014;16(1):e9628.