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ORIGINAL ARTICLE

High-frequency hearing thresholds: effects of age, occupational ultrasound and noise exposure

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Abstract
Purpose It has been suggested that high-frequency audiometry (HFA) could represent a useful preventive measure in exposed workers. The aim was to investigate the effects of age, ultrasound and noise on high-frequency hearing thresholds.
Methods We tested 24 industrial ultrasound-exposed subjects, 113 industrial noise-exposed subjects and 148 non-exposed subjects. Each subject was tested with both conventional-frequency (0.125–8 kHz) and high-frequency (9–18 kHz) audiometry.
Results The hearing threshold at high frequency deteriorated as a function of age, especially in subjects more than 30 years old. The ultrasound-exposed subjects had significantly higher hearing thresholds than the non-exposed ones at the high frequencies, being greatest from 10 to 14 kHz. This hearing loss was already significantly evident in subjects with exposure <5 years and increased with years of exposure and advancing age. The noise exposure group had significantly higher hearing thresholds than the non-exposed group at the conventional frequencies 4 and 6 kHz and at the high frequency of 14 kHz. After stratification for age, there was a significant difference between the two groups at 9–10 and 14–15 kHz only for those under 30 years of age.
Conclusion Multivariate analysis indicated that age was the primary predictor, and noise and ultrasound exposure the secondary predictors of hearing thresholds in the high-frequency range. The results suggest that HFA could be useful in the early diagnosis of noise-induced hearing loss in younger groups of workers (under 30 years of age).

Keywords High-frequency audiometry · Noise-induced hearing loss · Occupational noise exposure · Occupational ultrasound exposure · Early detection of noise impairment

Introduction

Many research articles have reported that hearing thresholds at frequencies above 8 kHz are reliable and that the sensitivity of the human ear to high-frequency sound decreases with increasing age and frequency (Ahmed et al. 2001; Lopponen et al. 1991).

Most interest in high-frequency audiometry (HFA) in occupational medicine is based on the assumption that noise may initially introduce damage at frequencies above 8 kHz and hence that HFA is useful as an early indicator of hearing loss (Ahmed et al. 2001).

Already in the 1960–1970s, many studies reported temporary rises in the hearing threshold due to ultrasound, both in the laboratory (Dobroserdov 1967; Smith 1967) and in working conditions (Acton and Carson 1967; Laukli and Mair 1985). Some authors (Acton 1973, 1975, 1983; Acton and Hill 1977; Morton and Reynolds 1991; WHO 1977) believed that the hearing risk due to ultrasound is due to the audible components of high-frequency subharmonics which accompany ultrasound itself. In 1982, the WHO (1982) stated that there should no hearing effects after exposure to ultrasound less than about 120 dB; the temporary displacement of the threshold should occur after short exposure to ultrasound at 150 dB. Investigations of the hearing risk of workers exposed to high-frequency noise emitted by ultrasound devices have shown significant rises in hearing

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thresholds in the range 10–20 kHz with respect to age-matched control groups (Grezsik and Pluta 1986a, b; IRPA 1981). The results of audiometric tests performed before and after a period of 3 years of exposure to ultrasound devices show that, in the hearing range 14–17 kHz, there is not only a rise due to aging but also a further hearing loss of 2–5 dB. The dynamics of high-frequency hearing loss may be calculated as 1 dB/year in conditions of continual exposure (Grezsik and Pluta 1986a, b). Other possible effects reported in the literature (Acton and Hill 1977) cover a whole range of symptoms, known in the past as "ultrasonic sickness," which included excessive asthenia, headache, nausea, vomiting and, when ultrasound exposure was intense, also vertigo, loss of balance and dizziness. It has been shown that these subjective effects are probably due to high levels of high-frequency audible noise, usually by-products of industrial ultrasonic processes (Acton and Hill 1977), or to the subharmonics of ultrasonic frequencies.

In the last 15 years, many studies (Ahmed et al. 2001; Bartsch et al. 1989; Fausti et al. 1981a, b; Lee et al. 2005; Northern et al. 1972; Silvestri et al. 2001; Somma et al. 2008; Mehrparvar et al. 2011) have reported hearing damage to high frequency due to noise exposure. Ahmed et al. (2001) found that age and exposure to noise were the first and second predictive factors which affect high-frequency hearing thresholds. Morton and Reynolds (1991) also described poorer thresholds in those exposed to noise: Age stratification showed statistically significant differences in the two groups of younger subjects (10–19 and 20–29 years) at frequencies exceeding 14 kHz. Sataloff et al. (1967) also reported significant differences in the mean audiometric thresholds in noise-exposed and non-exposed subjects at 10, 12 and 14 kHz; Fausti et al. (1979, 1981a, b) found a definite hearing loss in noise-exposed versus control subjects at frequencies exceeding 12 kHz. Similar results were also reported by Gauz et al. (1986). Investigating the hearing of 200 subjects exposed to noise of about 100 dBA, Dieroff (1982) concluded that high noise levels cause hearing loss at high frequencies. In contrast with previous studies, Osterhammel (1979), Osterhammel (1980), and Osterhammel and Osterhammel (1979) did not find statistically significant differences between high-frequency hearing thresholds in noise-exposed subjects, who already revealed deficits at 4 and 6 kHz, and non-exposed subjects.

The role of HFA in detecting ototoxicity has also been investigated, and the same conclusions were reached (Ahmed et al. 2001; Bartsch et al. 1989). Several authors believe that exposure to noise affects both high-frequency thresholds and conventional frequencies (especially 10, 12 and 14 kHz); in addition, high-frequency hearing deteriorates with increasing age and exposure to noise (Ahmed et al. 2001; Sulkowski et al. 1994).

The aim of this study was to investigate the effects of age and occupational exposure to ultrasound and noise on high-frequency hearing thresholds.

Subjects and methods

The study was conducted on three groups of subjects, whose characteristics are listed in Table 1.

The control group was composed of 148 subjects with no occupational noise or ultrasound exposure (medical assistants, technicians, etc.) and no experience of impaired hearing (head injures, ototoxic drugs, infections).

The industrial ultrasound-exposed workers (24 subjects of which 9 smokers and 15 non-smokers) were selected from two factories, one making textiles and one optical spectacles frames, in which environmental ultrasound measurements had been taken previously with a Bruel and Kjaer phonometer with a 4,136 microphone connected to a Larson Davis 3,200 frequency analyzer. In the textile factory, six template sample cutters for labels (operating at 20 kHz) and two label-trimming machines (operating at 30 kHz) were monitored; in the spectacle frames factory, four welding machines and eight ultrasonic cleaning tanks were monitored.

The noise-exposed group (113 subjects of which 69 smokers and 44 non-smokers) was composed of 23 workers from the same textile company as the group exposed to ultrasound: The former worked very close to the looms practically throughout their workshifts; the rest of the group was composed of 12 building workers, mainly manual laborers, and 21 workers in a cement factory occupied in various tasks, mainly in a mechanical workshop. The other 57 subjects worked in various metal-working companies. All groups had otoscopically normal ears and reported

Table 1 Main characteristics of study subjects

	Controls	Exposure to ultrasound	Exposure to noise
Group			
Number	148	24	113
Men	62	2	93
Women	86	22	20
Age (mean ± SD)	33.70 ± 13	39.1 ± 7.6	39.88 ± 9.99
(Range) years	(15–59)	(25–55)	(19–66)
Duration of employment			
Years (mean ± SD)	–	11.9 ± 7.7	17.62 ± 10.85
(Range) years		(1–33)	(0.5–47)
Smoking	34	9	69
Men	16	1	60
Women	18	8	9

negative histories for middle ear disorders, familial hearing-related diseases and use of ototoxic drugs.

To investigate the role of HFA in early detection of noise-induced hearing loss (NIHL), 63 workers with hearing thresholds for both ears ≤25 decibel hearing threshold level (dBHTL) in the conventional-frequency range of 2–8 kHz were selected from the noise-exposed group (13 women and 50 men, mean age 35.61 ± 8.15 years and mean noise exposure of 13.17 ± 8.02 years). They were later compared with 63 subjects from the control group, matched for age (mean age 35.48 ± 7.33 years).

Hearing thresholds at all frequencies (2 Hz–18 kHz) were determined in both ears of each subject with a Labat Audiopack audiometer with standard headphones for traditional frequency range 2,000–8,000 Hz, and Sennheiser mod. HD 500 earphones (Wedemark, Germany) for high frequencies, 9,000–18,000 Hz range. Audiometry was conducted in a sound–proof room or in the factory, fulfilling the criteria for measuring hearing thresholds down to 0 dBHTL in the conventional range, prior to shift, 16 h after the last exposure to noise. Measurements were made with an ascending-descending technique (ISO, 1989) in 5-dB steps in both conventional (2, 3, 4, 6, 8 kHz) and extended high-frequency (EHF) (9, 10, 11, 12, 13, 14, 15, 16, 17, 18 kHz) audiometry. The audiometer was calibrated at decibel hearing level (dBHL), according to Italian norm UNI EN ISO 389-5 for reference equivalent threshold sound pressure levels for pure tones in the frequency range 8–16 kHz, measured with Sennheiser earphones. Calibration of 17 and 18 kHz frequencies, not present in the standard, has been obtained from the manufactures by interpolation from the values reported by the norm on other frequencies.

For reproducibility testing, a group of 10 subjects (median age 28.5 years) was tested twice in 1 week and the differences between the two measurements were used to calculate the standard deviation (SD) at each frequency in both low and high ranges.

Possible occupational and risk factors for hearing loss were investigated, together with subjective effects such as asthenia, headache, gastrointestinal symptoms, tinnitus, sensation of fullness in the ears, low hearing, loss of equilibrium, vertigo and tingling in the hands and legs.

Descriptive statistics, means and SD were calculated to describe tendencies in each group. Multiple linear regression analysis was applied to determine the most important predictors of the hearing thresholds for each of the conventional and high frequencies tested. Independent variables were duration of noise exposure (years), age (years), gender and smoking. The Mann–Whitney nonparametric test was used to evaluate differences between group means. A p value of <0.05 was taken as statistically significant. Subjective effects were evaluated by χ^2 analysis.

The research was based on data gathered during health surveillance for workers, according to Italian law; therefore, approval by an ethics and scientific committee was not required. The workers were been verbally informed on the use of anonymous and shared data, in accordance with the Italian Privacy Law (Legislative Decree 196/2003).

Results

Reproducibility testing and age effects

Reproducibility testing of 10 subjects was performed in both frequency ranges for reasons of comparison. The SD of the differences varied between 0 and 6.12 dB at conventional frequencies and between 1.05 and 11.05 dB at high frequencies. This finding indicates that the variation in hearing thresholds at high frequencies was only slightly greater than that at conventional frequencies, so that intra-subject reproducibility at high frequencies could be compared with that at conventional ones.

Non-exposed subjects, subdivided for each decade of age, were as follows: 34 subjects aged 15–19 (mean age 17.1 years), 24 aged 20–29 (mean age 26.2 years), 37 aged 30–39 years (mean age 33.2 years), 33 aged 40–49 years (mean age 44.4 years) and 20 aged 50–59 years (mean age 54.1 years). Figure 1 shows the hearing thresholds of the non-exposed group at all frequencies. The trend clearly shows that high-frequency thresholds decreased with increased age and were more marked in the third age group (range 30–39 years) up to 14 kHz. At conventional frequencies, hearing thresholds were similar in all age groups up to the age of 50; in the older groups, the differences also involved 6 and 8 kHz, the frequencies of presbyacusia. Table 2 lists the mean ± SD of hearing thresholds (dBHL) of non-exposed subjects by age group.

The SD was generally greater at high frequencies (especially in the 11–15 kHz range) than at conventional ones and increased with advancing age. This indicates that inter-subject variability in the high-frequency range was greater than that at conventional frequencies, especially in the oldest groups (subjects aged 40–49 and 50–59 years).

Ultrasound effects

The group comprised 14 subjects recruited in a spectacle frames factory where there were four welding machines (three Branson welders, operating frequency 30 kHz, and one Schoeller, operating frequency 25 kHz); subjects worked continuously at a distance of 30–40 cm from the machines and non-continuously in front of the cleaning tanks. The other 10 subjects were employed in a textile factory; subjects worked at a distance of 30–40 cm from all

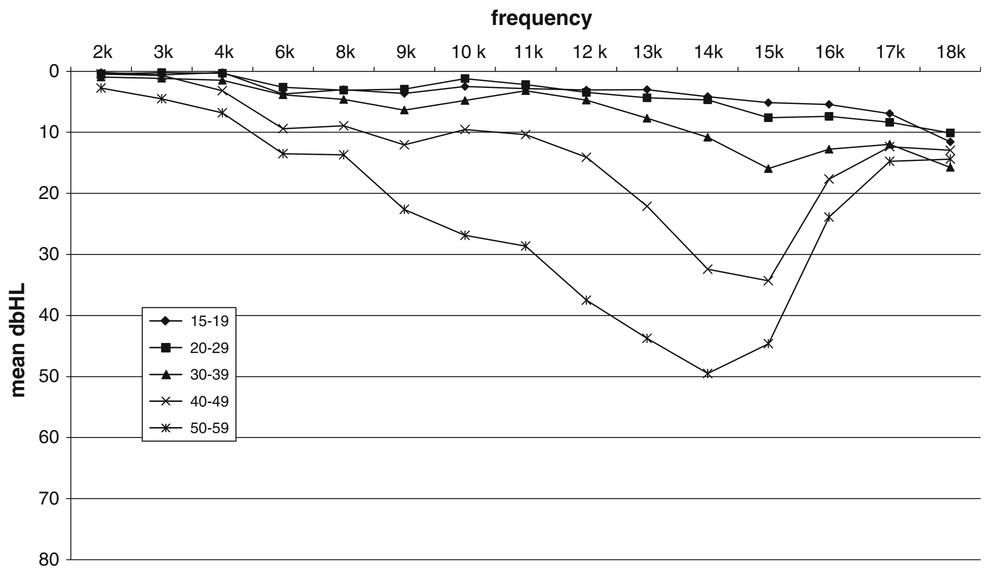

Fig. 1 Mean hearing thresholds of 148 non-exposed subjects in various age group

the machines. They all had ear protectors, but used them minimally; the shift was 6 h and 30 min in a day. The intensity levels measured near the ears of subjects exceeded the TLV-C (threshold limit value-ceiling) proposed by ACGIH (American Conference of Industrial Hygienists) in all sample cutters and label-trimmers at nominal frequencies of 20, 31.5 and 40 kHz, and in two of the cleaning tanks at frequencies of 20 and 25 kHz. All ultrasound emissions were accompanied by subharmonics produced in the audible high-frequency range as by-products of industrial ultrasonic processes.

The main results of multiple regression analysis of 24 ultrasound-exposed subjects and 148 control subjects are given in Fig. 2, which also shows the most important predictors, together with the associated total multiple R^2 and the percentage of stepwise increase in R^2.

Age and ultrasound exposure were found to be primary and secondary predictors, respectively, at all high frequencies tested. Age accounted for 5.3–62 % of the variation in hearing thresholds; ultrasound exposure accounted for 0.71–13.46 %. At conventional frequencies, age accounted for fewer variations, 8.2–30.3 %, and ultrasound exposure for 2.07–14.1 %. Gender and smoking showed no influence.

To study auditory effects, 24 controls of the same age were compared (16 women and 8 men, mean age 39.5 ± 7.9 years; range 25–55 years). Data were analyzed with the Mann–Whitney nonparametric test. The ultrasound-exposed subjects had significantly higher hearing thresholds ($p < 0.001$) than the non-exposed group, from 10 to 14 kHz, being greatest at 12, 13 and 14 kHz (Table 3). This hearing loss was already significant in subjects exposed for <5 years and increased with years of exposure and advancing age. No significant differences were found at conventional frequencies (0.5–8 kHz).

As regards subjective effects, asthenia and vertigo were significantly more frequently reported by the exposed group (χ^2 analysis) (Table 4).

Noise effects

One hundred and thirteen subjects exposed to industrial noise were tested.

The Lep,d of all workers were supplied directly by the management of factories; for all subjects, Lep,d was >80 dB(A) and mainly ranged between 98 and 100.7 dB(A) for the textile workers, between 80 and 88.5 dB(A) for the cement factory workers, and between 80 and 87.5 dB(A) for the building and metal-working workers. Both textile and cement workers reported constant use of protective devices, particularly tailor-made earplugs for the loom workers, and types varying from silicon plugs to muffs for the cement workers; the building workers reported irregular use of such devices.

Figure 3 shows the results of analysis of variance, carried out with multiple regression to study the simultaneous effects of the variables years of noise exposure, age, gender and smoking, on hearing thresholds, and which variables most greatly influenced hearing loss, at both traditional and high frequencies, in 113 noise-exposed subjects and 148 controls.

In this case too, at high frequencies, age was the main factor predicting hearing loss with respect to years of noise exposure. In high-frequency range, R^2 due to age varied

Table 2 Audiometric thresholds in dBHL (mean ± SD) of non-exposed subjects, subdivided by age

Frequency (kHz) Age group	2	3	4	6	8	9	10	11	12	13	14	15	16	17	18
15–19	0.21 ± 1.01	0.57 ± 2.49	0.21 ± 1.33	3.71 ± 6.52	3 ± 5.11	3.64 ± 5.31	2.5 ± 4.79	2.86 ± 5.81	3.07 ± 6.61	3 ± 6.62	4.14 ± 7.069	5.14 ± 7.81	5.42 ± 8.59	6.93 ± 9.97	11.57 ± 12.41
20–29	0.54 ± 2.17	0.22 ± 1.03	0.43 ± 1.77	3.15 ± 6.35	2.77 ± 5.51	3.04 ± 4.99	0.87 ± 2.85	1.41 ± 3.27	3.04 ± 5.63	4.45 ± 8.83	4.56 ± 8.29	7.17 ± 10.25	6.96 ± 9.80	7.39 ± 9.98	9.45 ± 9.14
30–39	2.26 ± 5.42	2.54 ± 6.09	2.92 ± 6.75	6.51 ± 10.07	5.47 ± 7.73	6.23 ± 7.06	4.25 ± 5.91	2.83 ± 5.24	4.52 ± 8.73	7.17 ± 9.33	8.77 ± 10.83	15.28 ± 12.98	14.8 ± 11.47	14.05 ± 10.24	16.88 ± 9.21
40–49	0.25 ± 1.12	1 ± 3.48	3.5 ± 8.12	10 ± 9.46	10.87 ± 11.2	10.75 ± 8.47	6.5 ± 9.33	7 ± 11.63	10.5 ± 14.03	15.25 ± 13.22	23.75 ± 13.94	33.75 ± 10.87	25.5 ± 10.87	25.75 ± 10.16	22.75 ± 7.51
50–59	2.5 ± 3.98	7.5 ± 8.91	5 ± 7.39	22.91 ± 10.1	16.46 ± 11.46	25 ± 15.95	29.16 ± 19.98	30.4 ± 16.30	44.58 ± 15.73	45.41 ± 13.56	48.33 ± 12.31	52.5 ± 5.83	38.33 ± 4.43	32.5 ± 7.23	25.42 ± 4.50
Total 148	0.97 ± 3.30	1.51 ± 4.59	1.59 ± 4.99	6.09 ± 9.31	5.18 ± 8.07	6.17 ± 8.77	4.58 ± 9.51	4.58 ± 9.66	6.66 ± 13.07	8.18 ± 13.53	10.05 ± 14.7	13.95 ± 16.37	12.21 ± 13.28	12.31 ± 12.48	14.42 ± 11.17

from 9.6 to 64.5 %, whereas years of work contributed from 1 to 3.4 %. Instead, at traditional frequencies, the order of significance was inverted. In this frequency range, particularly from 2 to 6 kHz, age had less effect, with values from 3.3 to 11.7 %, while years of noise exposure was the main predictive factor, ranging from 30.8 to 42.2 %. In this case too, multivariate analysis essentially showed how age dominates the effect of working exposure at high frequencies. Smoking and gender accounted for 0.6 % at 11 kHz and 1 % at 12 kHz, for 0.5–1.1 % from 3 to 8 kHz, and for 5.5–2.9 % at 9 and 10 kHz, respectively. Here too, this influence may be viewed as almost negligible, since it was close to zero.

The values for noise-exposed subjects compared with 113 controls of the same age (mean 39.71 ± 10.67 years) are shown in Fig. 4 (data analyzed with Mann–Whitney nonparametric test; $p < 0.05$).

The noise-exposed group had significantly higher hearing thresholds ($p < 0.001$) than the non-exposed group at conventional frequencies from 2 to 6 kHz, with $p < 0.05$ at 8–9 and 14–15 kHz. Table 5 lists high-frequency audiometric curves of both groups subdivided according to decade of age and shows that noise-exposed subjects had a statistically significant higher hearing threshold than non-exposed subjects: at 9, 10, 13, 14 and 15 kHz until the age of 30; at 9, 14 and 15 kHz until 40; at no high frequency between 40 and 49; they then returned to significant levels at 14, 15, 17 and 18 kHz between the ages of 50 and 59. However, in the last group, hearing loss at these frequencies was >40 dB. Instead, for conventional frequencies, statistically significant differences were observed from the age of 40 onward.

Table 6 shows the hearing thresholds of noise-exposed subjects by years of noise exposure.

The differences between the hearing thresholds at high frequencies were statistically significant for those with fewer than 10 years of work at 9, 10, 14 and 15 kHz, but, for those exposed for longer than 10 years, there was no statistically significant difference at high frequencies and the trends of the two groups overlapped. This confirms that age plays a predominant role with respect to working noise exposure. As regards conventional frequencies, the greatest differences between the curves appeared for subjects exposed for more than 20 years to frequencies between 2 and 6 kHz.

Lastly, Fig. 5a–d compares 63 workers with hearing thresholds in both ears of ≤25 dBHTL and 63 age-matched controls, divided into four subgroups according to age: 24 subjects aged 20–29, 23 of 30–39 and 16 of 40–49.

The curves show that only in the first group—noise-exposed subjects aged 20–29 and their controls—were there statistically significant differences in high-frequency thresholds, i.e., 9, 10, 13, 14 and 15 kHz (p values of 0.01,

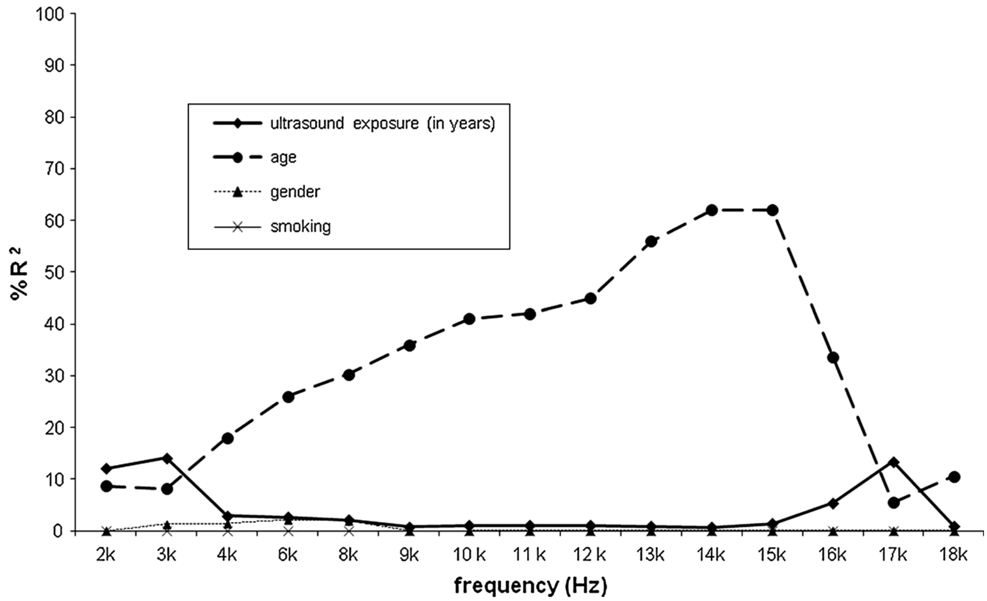

Fig. 2 Results of multiple regression analysis of hearing thresholds values of 24 ultrasound exposure subjects and 148 controls, showing predictors and the percentage of the stepwise R^2 for each predictor

0.001, 0.02, 0.0024 and 0.02, respectively). The curves of older exposed subjects did not show statistically significant differences at either high or conventional frequencies. Also evident was the progressive hearing loss at high frequencies with age. Table 7, listing the main subjective symptoms of noise-exposed workers versus controls, shows how almost all the symptoms occurred mainly in the exposed group, apart from asthenia, gastrointestinal disorders and vertigo (3.6 vs 5.9 %; 7.1 vs 16.66 % and 1.8 and 3 %, in exposed subjects and controls, respectively).

Statistical analysis (χ^2) showed that the noise-exposed group had statistically significant more problems of tinnitus and hearing loss. Significant correlations were also shown between the group of workers exposed to tinnitus, sensation of fullness in the ears and hearing loss >25 dB at 4 kHz.

Discussion

Reproducibility and age effects in high-frequency audiometry

As regards reproducibility, several authors (Dreschler et al. 1985; Frank 2001; Northern et al. 1972; Osterhammel 1979; Osterhammel and Osterhammel 1979) have reported similar results, indicating that the reliability of high-frequency hearing thresholds is comparable to that of conventional frequencies and that HFA can be used to monitor hearing thresholds.

The audiograms of the 15- to 19- and 20- to 29-year-old groups were similar at all frequencies tested; in subjects over 30, sensitivity to high frequencies decreased, especially over 15 kHz, and, with increasing age, the reduction in the hearing threshold also involved the lowest frequencies in the 9–16 kHz range. The frequencies 17 and 18 kHz were not changing with age; probably, this was due to the type of calibration. None of the previous HF audiometers used in published papers had been calibrated in dBHL, being in dBSPL, but ours was calibrated in dBHL according to Italian norm UNI EN ISO 389-5. It was possible to compare only the general trends of threshold sensitivity at high frequencies but not the single data.

At conventional frequencies, thresholds changed only in the oldest groups (subjects aged 50–59). The mean hearing thresholds at high frequencies reported in this study are higher than those reported by other researchers, due to the different calibration of the audiometer, but the finding that the increase in hearing threshold is age-dependent endorses previous results (Ahmed et al. 2001). Ahmed et al. showed that 99 % of non-exposed subjects under the age of 40 were responsive up to 14 kHz, and this percentage fell to 91 and 76 % at 16 and 18 kHz, respectively (Ahmed et al. 2001). Similar results were reported by Rosen et al. (1964) and Sataloff et al. (1984). Northern et al. (1972) reported that 90 % of their subjects under 40 years responded to frequencies up to 14 kHz, 80 % up to 16 kHz and none at 18 kHz. For Somma et al. (2008), all non-exposed workers younger than 40 responded to all the given pure tones, with both conventional audiometry and HFA. For these authors, threshold changes at high frequencies with age were noticeably more marked over the age of 40, whereas we found some differences at over 30 but more marked ones at over 40.

Table 2 lists the mean ± SD of hearing thresholds (dBHL) of the non-exposed group, which are similar to results from other authors (Ahmed et al. 2001;

Table 3 Audiometric thresholds in dBHL (mean ± SD) of 24 subjects subjected to ultrasound, paired with 24 controls by age

Subjects	Frequency (kHz)														
	2	3	4	6	8	9	10	11	12	13	14	15	16	17	18
Non-exposed	0.94 ± 2.45	1.67 ± 4.168	1.98 ± 6.17	8.44 ± 11.02	7.5 ± 10.49	10.41 ± 10.81	7.08 ± 11.93	7.08 ± 13.40	10.52 ± 17.9	13.43 ± 17.32	18.02 ± 17.78	25.94 ± 17.85	19.17 ± 13.58	18.54 ± 13.37	17.29 ± 8.18
Exposed	3.54 ± 6.27	5.42 ± 9.83	6.15 ± 10.43	13.12 ± 11.7	12.34 ± 12.5	14.90 ± 14.6	16.98* ± 14.61	16.87* ± 14.9	23.12* ± 19	27.71* ± 18.9	33.02* ± 19.28	34.90 ± 19.11	25.1 ± 13.66	21.67 ± 11.95	23.02 ± 8.79

* $p < 0.001$

Table 4 Prevalence of subjective symptoms in number (*n*) of subjects exposed to ultrasound, with respect to controls

Subjects	*n*	Asthenia (%)	Headache (%)	Nausea (%)	Stomach pain (%)	Vomiting (%)	Tinnitus (%)	Sensation of fullness (%)	Hypoacusia (%)	Uncertain gait (%)	Vertigo (%)	Sleep disorders (%)	Tingling in limbs (%)
Exposed	14	33	66	12.5	15.84	4.1	20.8	8.3	12.5	4.1	25	20.8	29.16
Controls	101	5.9	45.54	8.9	16.66	0	12.87	5.9	2.9	2	3	7.9	5.9

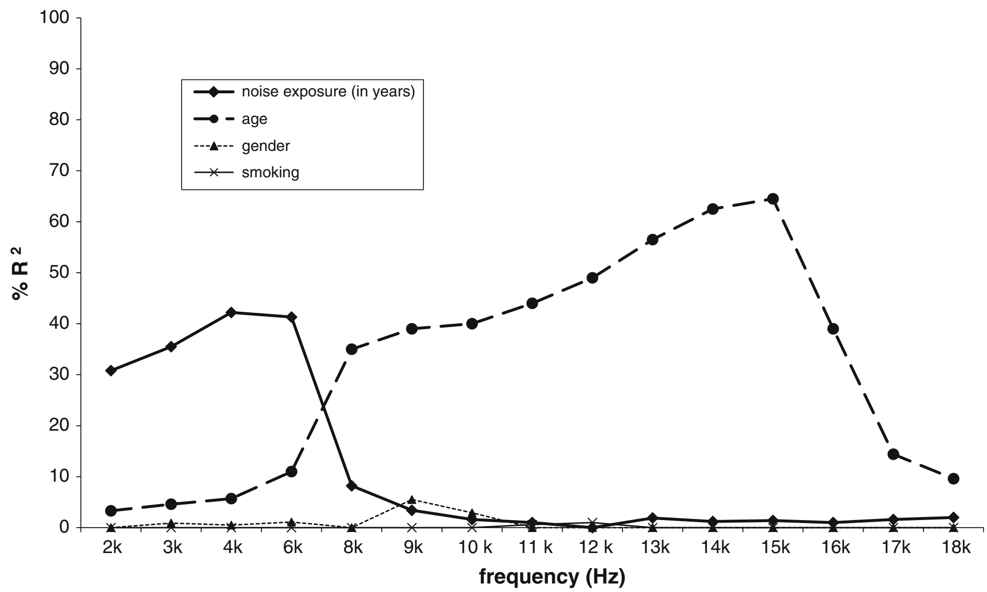

Fig. 3 Results of multiple regression analysis of hearing thresholds values of 113 noise exposure subjects and 148 controls, showing predictors and the percentage of the stepwise increase in R^2 with total multiple R^2 for each predictor

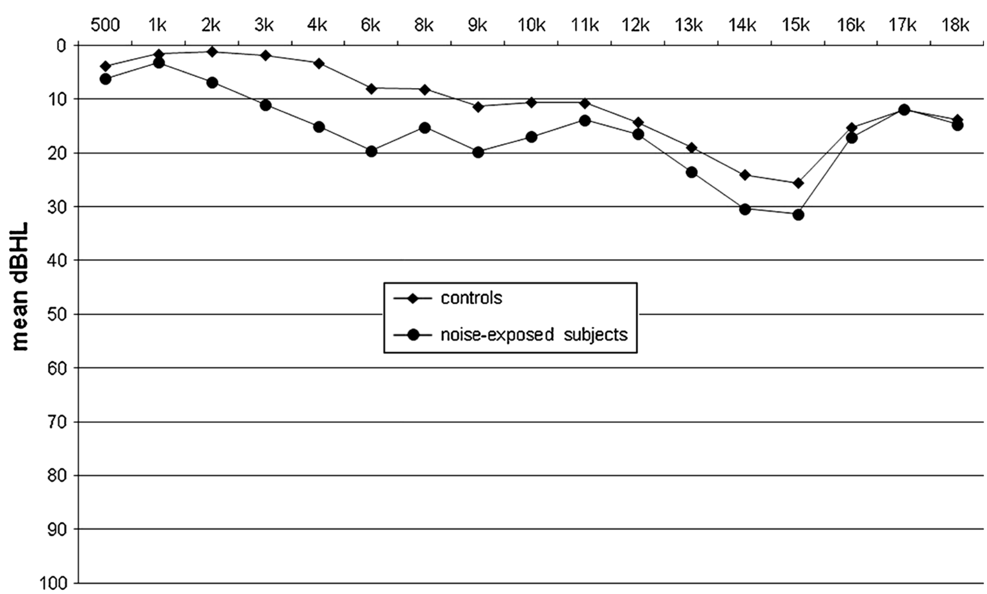

Fig. 4 Mean hearing thresholds of 113 noise-exposed subjects versus 113 age-matched controls

Dreschler et al. 1985; Northern et al. 1972) who reported high SD ranging from 10 to 20.7 dB for the high-frequency range (10–18 kHz) and from 2.4 to 14.5 dB for conventional frequencies. Smaller ranges were reported by Ahmed et al. after excluding subjects who did not respond at 16 and 18 kHz, SDs ranging between 4.6 and 5.6, mean 4.8 (Ahmed et al. 2001).

It was because of this variability that each of the above authors chose their own control group: in particular, Laukli and Mair (1985) chose a small number of subjects aged between 20 and 24 as reference group, whereas Fausti et al. (1979, 1981a, b) found that the hearing sensitivity above 12 kHz to be highly variable for unknown reasons; they concluded that, as reference group, the best audiometric thresholds of a group of young adults are preferable at high frequencies, rather than the mean of all those examined. They thus chose the 30 best ears in a group of 100 young adults. In agreement with the above authors, Ahmed et al. (2001) and Morton and Reynolds (1991) also chose the 20 best ears from a total of 104 subjects not exposed to ototoxic agents. However, the above authors report differing mean hearing thresholds (in some cases higher, in others

Table 5 Comparison of means of hearing thresholds between non-exposed and noise-exposed groups at high frequencies (9–18 kHz) in dBHL, by age group (in years)

Age group	Mean ± SD	Frequencies in kHz									
		9	10	11	12	13	14	15	16	17	18
19–29	Non-exposed	2.86	1.43	2.32	3.57	4.17	4.88	7.02	6.55	8.27	8.93
	Exposed	8.45*	6.55*	3.57	6.07	10.95*	14.64*	15.83*	8.21	6.31	8.21
30–39	Non-exposed	6.71	4.86	2.93	4.71	7.71	10.79	15.50	12.14	11.43	12.21
	Exposed	12.29*	9.00	6.29	8.14	13.36	20.64*	23.10*	11.64	7.14	15.50
40–49	Non-exposed	12.05	9.55	10.38	14.09	22.12	32.42	34.32	17.65	12.35	12.95
	Exposed	18.03	15.53	10.76	13.33	22.65	33.11	36.44	19.77	11.52	15.76
50–59	Non-exposed	22.6	26.9	28.6	37.5	43.8	49.5	44.6	23.9	14.8	14.4
	Exposed	41.1*	37.8	37.1	41.8	50.9	56.4*	51.8*	29.8	23.6*	23.1*

* $p < 0.05$

lower) with respect to those given in other studies, probably due to the different audiometers used. Like Osterhammel (1980), we believe that the reference levels of high-frequency hearing thresholds must be stratified by age.

Ultrasound effects

Our data show that, in some situations, the ACGIH threshold values for ultrasound are exceeded, representing a risk factor for exposed workers.

Hearing effects

As regards hearing effects, overall our results show that exposure to ultrasound damages hearing in the frequency range 9–18 kHz, that this deficit may already appear after work exposure of <5 years and that it worsens with continued work exposure and with age.

Results similar to ours, involving the central frequencies in the high-frequency range, were obtained in several studies (Grezsik and Pluta 1983, 1986a). Their authors believed that hearing damage depends on the spectral characteristics of ultrasound, the number of years of exposure to it and the duration of daily exposure. In the second work quoted above (Grezsik and Pluta 1986a), the authors concluded that prolonged exposure to sound levels over 80 dB for 8 h a day for 15 years leads to a hearing loss of between 10 and 16 kHz. In the third work (Grezsik and Pluta 1986a), the authors compared two series of audiograms taken at a 3-year interval, of 55 workers exposed to ultrasound, finding a rise in the hearing level due only to aging in the frequency ranges between and 0.5–8 kHz and 10–13 kHz. Instead, they found a rise from 2 to 5 dB higher than that due to aging in the range 14–17 kHz and estimated that, at these frequencies, the additional deficit was 1 dB/year in conditions of constant exposure. Further hearing damage attributable to ultrasound was also found by Sulkowski in 1994 and in other recent studies (Silvestri et al. 2001).

Subjective effects

All the symptoms were found in the exposed group to ultrasound with respect to controls, apart from gastrointestinal disorders (15.84 vs 16.66 %, respectively, in exposed subjects and controls), although statistical analysis revealed a significance difference for two of the symptoms typical of ultrasound exposure: asthenia and vertigo (χ^2 test). Asthenia mainly occurred once a week and vertigo about once a month, both at the end of the workshift or during it. Histories also showed that the symptoms persisted for a few days after exposure had ceased and no longer occurred in the absence of exposure.

Many studies have described this type of symptoms in subjects professionally exposed to ultrasound (Allen et al. 1948; Crawford 1995; Skillern 1965).

In 1967, Acton et al. stated that, in the case of cleaning tanks operating at 20 kHz (equal to 95 dB) with harmonics at 40 kHz (115 dB), the workers complained of fatigue, buzzing noises, nausea and headache, persisting for some hours after the end of exposure; when the tanks were closed and emissions fell to 10 dB, these effects disappeared. In 1981, IRPA reported that several subjective effects (including audible effects) were due to the subharmonic components of ultrasound, rather than to ultrasound itself. In 1982, the WHO stated that ultrasound may induce nausea, vomiting, fatigue, headache and a sensation of fullness and pressure in the ear. In 1983, Acton again reported that the complaints of workers exposed to ultrasound included sensations of fullness and pressure in the ear, followed by fatigue, nausea and tinnitus. Loss of balance appeared to depend more on audible noise than on ultrasound. In 1981, IRPA reported that the most

Table 6 Comparison of audiometric thresholds of 113 noise-exposed subjects, subdivided by years of work, paired with 113 age-matched controls

Years of employment	Mean ± SD	Frequencies in kHz														
		2	3	4	6	8	9	10	11	12	13	14	15	16	17	18
<10 years	Non-exposed	0.5	0.7	0.8	4.6	5.0	6.4	4.9	4.4	7.0	9.9	12.2	13.7	10.6	9.6	12.7
	Exposed	2.9	4.9	6.3	11.4	9.7	14.2*	11.9*	9.3	11.4	16.4	22.1*	23.2*	11.9	8.0	11.3
11–20 years	Non-exposed	1.1	1.5	2.1	6.5	5.7	7.8	6.5	5.4	7.9	10.5	14.1	17.7	12.5	10.9	13.8
	Exposed	3.3	6.6	10.2	13.4	8.3	14.2*	10.7	7.8	10.2	15.5	22.2	24.7	12.9	7.6	11.4
21–30 years	Non-exposed	1.03	0.78	4.31	9.74	10.39	14.31	12.5	14.7	17.7	25.7	35.3	37.2	19.2	13.4	13.9
	Exposed	8.02*	11.9*	17.7*	23.3*	19.01	20.43	18.4	14.7	18.1	28.0	38.6	40.5	21.8	13.9	17.9
31–44 years	Non-exposed	3.75	5.00	7.75	13.21	18.39	18.93	28.8	31.8	35.5	44.7	48.4	50.8	37.3	21.4	16.8
	Exposed	22.7*	35.2*	43.0*	47.5*	38.3*	46.2*	42.86	38.93	42.32	51.61	54.82	49.96	31.07	27.68	24.82

* $p < 0.05$

significant indicators of ultrasound damage were subjective effects: fatigue, headache, nausea, tinnitus, sensation of fullness and pressure in the ear, uncertain gait, vertigo and sleep disorders.

Noise effects

Noise-induced hearing loss is an irreversible disorder and a common problem in industrial settings. An early diagnosis of it can help to prevent the progression of hearing loss and reduce possible social problems arising from hearing loss in speech frequency. Usually for early diagnosis, audiometry is performed in conventional frequency, but it has been reported that noise may initially introduce damage at frequencies above 8 kHz (Ahmed et al. 2001). Table 8 shows the recent papers with the most important results to HFA and noise occupational exposure.

Matching our results in Fig. 3, Ahmed et al. also found that age and exposure to noise were the first and second predictive factors which affect high-frequency hearing thresholds; they reported an R^2 at high frequencies for age varying between 80 and 87 %, and for noise between 7 and 18 %. At conventional frequencies, the order of significance in their multivariate analysis, like ours, was inverted (noise affected 79–86 % of subjects, followed by age, 14–18 %). Somma et al. (2008) also reported similar results; their linear regression analysis, subdivided by age group, showed that workers aged between 21 and 40 were mainly affected at all frequencies (except at 18 kHz), whereas in those over 40 noise affected them more up to 6 kHz and the effect of age predominated at high frequencies.

In our current study, comparisons of audiometric curves of noise exposed and controls show statistically significant differences at 9–10 and 14–15 kHz. The frequency of 14 kHz appears to be the level most frequently involved in noise exposure, also in other studies (Ahmed et al. 2001; Morton and Reynolds 1991; Silvestri et al. 2001). The subdivision according to decade of age (Table 5) shows how noise-exposed subjects have higher statistically significant hearing thresholds at high frequencies, compared with non-exposed subjects, mainly until the age of 30, and 40 onward at conventional frequencies. The age stratification used by Ahmed et al. (2001) showed statistically significant differences in high-frequency hearing thresholds with respect to controls, even in subjects aged 20–29. With increasing age, the mean hearing thresholds of the two groups began to converge, particularly at 16 and 18 kHz, and then overlapped at all high frequencies in the fourth age decade (40–49 years); however, the mean age of their subjects was significantly higher than that of the controls.

Hallmo et al. (1995) found that in the youngest (18–24 years), who had the lowest degree of hypoacusia at

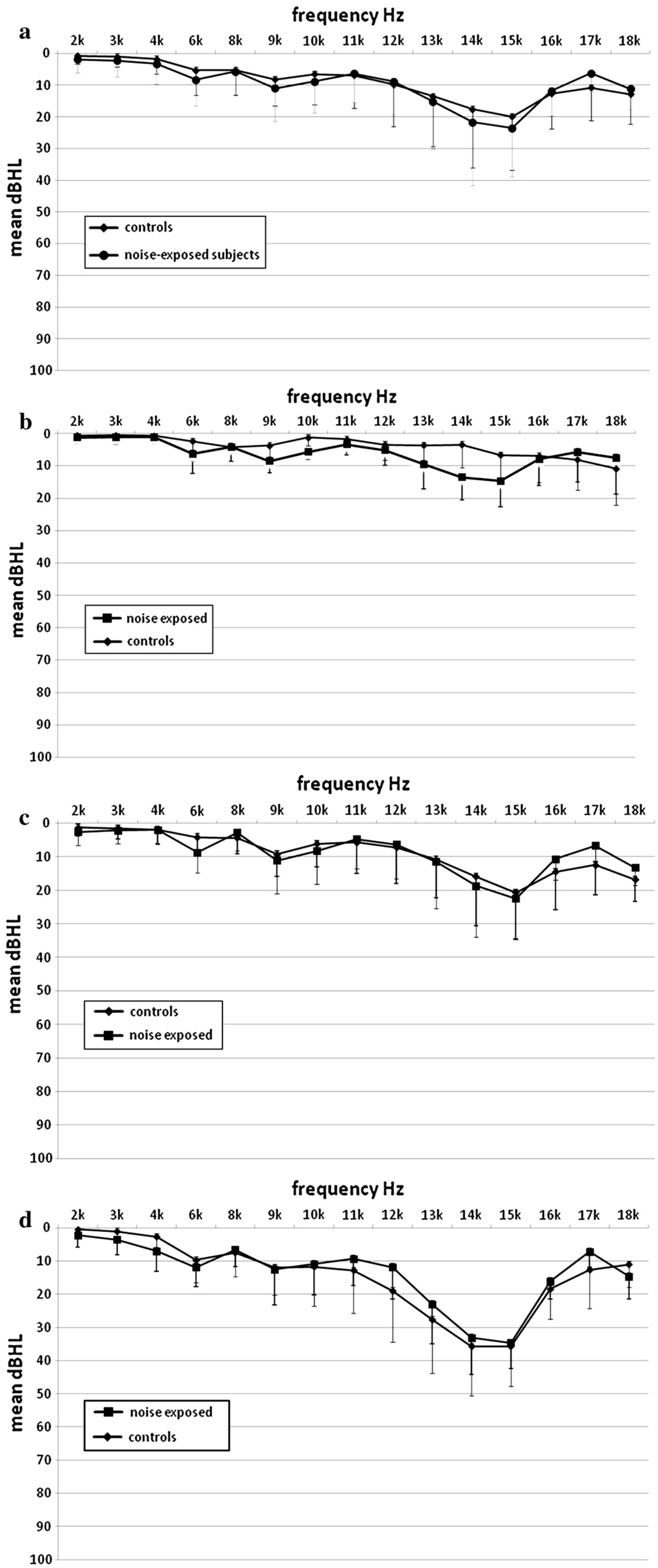

Fig. 5 **a** Mean hearing threshold of 63 noise-exposed subjects with dBHL ≤25 dBA in conventional range and 63 age-matched controls. **b** Mean hearing threshold of 29 noise-exposed subjects (age 21–30 years) with dBHL ≤25 dBA in the conventional range and 29 age-matched controls. **c** Mean hearing threshold of 23 noise-exposed subjects (age 31–40 years) with dBHL ≤25 dBA in the conventional range and 23 age-matched controls. **d** Mean hearing threshold of 16 noise-exposed subjects (age 41–50 years) with dBHL ≤25 dBA in the conventional range and 16 age-matched controls

Table 7 Prevalence of subjective symptoms in noise-exposed subjects versus controls

Subjects	*n*	Asthenia (%)	Headache (%)	Nausea (%)	Stomach pain (%)	Vomiting (%)	Tinnitus (%)	Sensation of fullness (%)	Hypoacusia (%)	Uncertain gait (%)	Vertigo (%)	Sleep disorders (%)
Exposed	5	3.6	35.7	12.5	7.1	1.8	32	12.5	25	3.6	1.8	16.1
Controls	101	5.9	45.54	8.9	16.66	0	12.87	5.9	2.9	2	3	7.9

conventional frequencies, had a mean hearing loss of 20 dB in the range 8–18 kHz, when compared with the control group of equal age.

Somma et al. (2008) reported that high-frequency hearing loss is linked to age, progressing to traditional frequencies with increasing age, and noted how these changes are accentuated during the first years of exposure to noise.

Our study, like those in the literature, shows how the effects of age and noise are additive at high frequencies (like conventional ones) and that the effect of age predominates over that of noise (mainly in subjects over 40).

Other authors (Osterhammel 1979, 1980; Dieroff 1982) concluded that presbyacusia and damage due to noise had an additive effect, particularly in subjects over 50, but those with abnormal high-frequency hearing thresholds may be more sensitive to noise damage. Other contradictory evidence was produced by Laukli and Mair (1985), who found good high-frequency thresholds in young subjects exposed to industrial noise. However, they did not report the thresholds of the same subjects to conventional frequencies.

As regards years of exposure to occupational noise, in which significant differences are found in subjects working for <10 years at high frequencies and 20 years at conventional ones, similar results were reported by Riga et al. (2010).

Lastly, assessing the reliability of HFA as an early indicator of NIHL (Fig. 5) showed that only in the first group (up to the age of 29) there are statistically significant differences in high-frequency thresholds and that a progressive, age-related hearing loss occurs later, so high-frequency audiometry can be used as an early indicator of damage in mainly young workers (under 30) exposed to noise (Mehrparvar et al. 2011; Ahmed et al. 2001; Fausti et al. 1979, Fausti et al. 1981a, b; Gauz et al. 1986; Northern et al. 1972).

Ahmed et al. (2001) reported that the high-frequency hearing thresholds of 23 noise-exposed subjects to traditional frequencies in the normal range (hearing deficit <20 dBHL) were higher at 12, 14, 16 and 18 kHz; age stratification showed statistically significant differences at high frequencies in subjects over the age of 25. Similar results were also reported by Morton and Reynolds (1991) and Fausti et al. (1979, 1981a, b), who concluded that HFA, giving more complete mapping of hearing sensitivity in the basal region of the cochlea, is an excellent method of highlighting NIHL from childhood until young adulthood. Later, other often unknown factors may accumulate during a subject's lifetime, causing considerable functional changes in high-frequency hearing thresholds, which limit the potential efficacy of the method in observing presumably future noise-induced variations at such frequencies.

Table 8 Summary of major existing studies about HFA and noise occupational exposure

References (year)	Noise exposure level	Study population	Frequencies analyzed	Variables examinated	Auditory effects	Conclusions
Bartsch et al. (1989)	80–84 dB (A) 85–90 dB (A) 90–94 dB (A)	537 exposed	0.5–18 kHz	Age Noise level Years of noise exposure	The range around 13 kHz frequency is of decisive importance as the deficit in conventional audiometry	HFA is important for early detection of noise hearing loss only for young person with normal hearing before any noise exposure
Hallmo et al. (1995)	–	167 exposed	0.25–8 kHz 10–18 kHz	Age Years of noise exposure	Threshold increase in HF is present in all age group and grades of conventional hearing loss	An age effects in HF range is present only in the lowest grades of conventional-frequency noise-induced hearing loss
Ahmed et al. (2001)	>85 dB (A)	260 exposed versus 99 controls	0.25–8 kHz 10–18 kHz	Age Exposure to noise Use of walkman devices Having noise hobbies	Higher hearing thresholds in all high frequency tested, greatest at 14 kHz	HFA might used as early indicator for noise hearing loss and acoustic trauma particulary for younger group
Somma et al. (2008)	>85 dB (A)	184 exposed versus 98 controls	0.25–8 kHz 9–18 kHz	Age Exposure to noise Smoking Hypertension	Higher hearing thresholds in subjects <40 years, at 14 and 16 kHz	HFA is an useful preventive measure in younger than 40 years exposed workers
Riga et al. (2010)	8 h at 90–110 dB (A)	151 exposed	0.25–8 kHz 10–18 kHz	Age Duration of employment	Significant thresholds shift at 12.5, 14, 16 kHz in workers with <10 years of employment	Implementing HFA audiometry in workers employed <10 years
Mehrparvar et al. (2011)	>85 dB (A)	120 exposed versus 120 controls	0.25–8 kHz 10–16 kHz	Gender	Higher hearing thresholds in all high frequency tested, the greatest at 16 kHz	HFA is useful for early diagnosis of hearing sensitivity to noise

Bartsch et al. (1989) found hearing deficits at 10 and 14 kHz even in subjects aged between 17 and 30, exposed to noise between 80 and 84 dB(A) for <10 years, and Riga et al. (2010) showed that significantly higher frequencies, raised by 2 and 4 kHz, were involved in the second decade and that, after 20 years of exposure, frequencies of 0.25, 0.5 and 1 kHz were involved. They concluded that HFA is useful in identifying the first signs of hearing loss even before conventional audiometry and that both methods should be used together, mainly in the first 10 years of exposure.

Conclusion

This study has shown that after the age of 30, hearing loss begins to occur at high frequencies exceeding 15 kHz, becoming more significant with age and extending to all high frequencies and to those at 6–8 kHz. Age was the primary predictor, and noise and ultrasound exposure the secondary predictors of hearing thresholds in high-frequency range.

Our study had some limitations because the exposition levels and time of the ultrasound and noise exposure groups are little documented and collected retrospectively directly by the management of the factories. However, the study has shown in ultrasound exposed, statistically significant differences from 10 to 14 kHz, in workers exposed for <5 years and a worsening with increasing years of work and age.

In noise exposed, statistically significant differences from 2 to 8 kHz and at high frequencies 9–10 and 14–15 kHz were found until the age of 39 and in subjects professionally exposed for <10 years, after which age plays the dominant role; at conventional frequencies, this rises to 20 years.

As regards the use of high-frequency audiometry as an early indicator of NIHL, there is still controversy in this issue, but most recent studies were consistent with our data; performing HFA could be useful in the early diagnosis of NIHL particularly in young subjects, under the age of 30, in addition with conventional audiometry.

Conflict of interest The authors declare that they have no conflict of interest.

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