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ORIGINAL ARTICLE

The rate of occupational noise-induced hearing loss among male workers in Israel and implication on hearing surveillance frequency

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Abstract

Objectives To investigate the annual rate of NIHL in Israel, a modern economy with relatively low industrial hazardous noise exposure. To review international protocols of hearing surveillance. To recommend an effective, efficient, hearing screening frequency protocol.

Methods A historical cohort study was conducted. Audiometric surveillance data from the Jerusalem occupational medicine registry of male employees in various industries from 2006 to 2017 were used. Mean individual annual threshold shifts simulating 1–8 checkup interval years were calculated. Joinpoint regression analysis was used to assess the interval in which the slope of the calculated ATS variability moderates significantly.

Results A total of 263 noise-exposed workers and 93 workers in the comparison group produced 1913 audiograms for analysis. Among the noise-exposed workers, using the 1–4 kHz average, threshold shifts stabilized from 3 years onwards at around 1 dB per year in all age groups and 0.83 dB in the stratum younger than 50 years. No enhanced decline was detected in the first years of exposure.

Conclusion Although most countries conduct annual hearing surveillance, hearing threshold shifts of noise-exposed workers become more accurate and show less variability when calculated at 3-year checkup intervals onwards than shorter intervals. Since margins of errors of the test method are much larger than the annual shift found, screening schedule that enables each subsequent test to identify a real deterioration in hearing is necessary. Triennial audiometric screening would be a better surveillance frequency for noise-exposed workers younger than 50 years of age in the category of 85–95 $dBL_{Aeq,8\ h}$ without other known risk factors.

Keywords Occupational noise-induced hearing loss · Annual audiometry · Threshold shift · Occupational surveillance frequency · Occupational noise exposure · Hearing conservation

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Abbreviations

ANSI	American National Standards Institute
dB	Decibel(s)
dBA	Decibel(s), sound pressure level, A-weighted
85$dBL_{Aeq,\ 8\ h}$	85 Decibels, A-weighted, for 8-h time-equivalent continuous sound level
HL	Hearing loss
Hr	Hour(s)
Hz	Hertz
kHz	Kilohertz
NIHL	Noise-induced hearing loss
NIOSH	National Institute for Occupational Safety and Health
OSHA	Occupational Safety and Health Administration
SNHL	Sensorineural hearing loss

STS	Significant or standard threshold shift
TWA	Time-weighted average

Introduction

Epidemiology

Occupational noise-induced hearing loss (NIHL) is a significant cause of potentially avoidable morbidity and one of the most prevalent work-related health hazards internationally, accounting for 16% of hearing loss (HL) in adults (Chadambuka et al. 2013; Lie et al. 2016; Rabinowitz 2012; Themann and Masterson 2019; Tikka et al. 2017). Pre-COVID-19, hearing impairment accounted for 10% of all non-fatal occupational diseases, and was ranked the second most common occupational condition reported in the US (United States Department of Labor Bureau of Labor Statistics 2019). Approximately 14–20% of workers in the US, Europe, and Australia are exposed to hazardous noise in their occupational settings and 16% of the exposed develop significant hearing impairments (Rabinowitz et al. 2011; Themann and Masterson 2019). Hazardous noise can be defined as sound intensity level, frequency, and duration above a particular exposure limit, thereby potentially harmful to hearing (Themann and Masterson 2019). Many countries, including Israel, use 85 $dBL_{Aeq,8\,h}$ (A-weighted, equivalent continuous sound over an 8-h period) as a cut-off for hazardous occupational noise which requires hearing surveillance for the exposed workers (Arenas and Suter 2014; Israel Ministry of Economy and Industry Labour 1984). A noise level of 85 $dBL_{Aeq,8\,h}$ represents 8% of acceptable excess risk over a 40-year working lifetime (NIOSH 1998; Bruce et al. 2010; Siegel 2019).

In Israel, about 24% of workers reported being exposed to hazardous noise levels at some point during their work life (Israel Central Bureau of Statistics (ICBS) 2016). However, Israel, like Europe, USA and other developed countries, is undergoing labor market changes characterized by transforming conservative industry to high technology and service sectors (Hartmann et al. 2021). As a result, fewer workers are exposed to hazardous noise, and those who are exposed experience relatively lower intensity levels. Nevertheless, occupational NIHL is still the most commonly reported occupational disease in Israel, constituting about 46% of all such disorders recorded in the National Registry of Occupational Diseases (Meiman et al. 2019).

Pathophysiological progression

NIHL is characterized by more prominent reduction at 3–6 kHz "noise sensitive area" compared to the surrounding frequencies (i.e., 2 or 8 kHz), with a typical antecedent, 4 kHz notch (Lie et al. 2016; Liebenberg et al. 2021; Mirza et al. 2018). In the early phases, noise affects high frequencies which are indiscernible in daily communication (Liebenberg et al. 2021; Mirza et al. 2018; Tikka et al. 2017). Hence, periodic hearing screening is vital for detecting subclinical changes (EU-OSHA 2005; Lie et al. 2016; Silva et al. 2022; Verbeek et al. 2014). Previous studies have demonstrated accelerated hearing deterioration among noise-exposed workers aged 50 and above, due to additional factors such as presbycusis (age-related hearing loss; Lie et al. 2016; Liebenberg et al. 2021). In addition, there is evidence in the literature for accelerated occupational NIHL in first years of occupational noise exposure, ranging from the first 3 to 15 years of exposure (Cantley et al. 2019; Mirza et al. 2018). Individual susceptibility to the higher rates of hearing deterioration in the first years of exposure vary; however, the reasons for the variation are not clearly established (Cantley et al. 2019).

Hearing conservation policies

Annual hearing surveillance is a major component of occupational hearing conservation programs and it is the default protocol used in many western countries (Davies et al. 2008; EU-OSHA 2005; Hannah et al. 2016), as demonstrated in Table 1.

In Israel, annual hearing surveillance is mandatory, under the Safety at Work Ordinance (Occupational hygiene and health of workers exposed to noise 1984), and applied to all workers exposed to hazardous occupational noise. Unlike most countries, the surveillance is covered by the National Health Insurance and provided universally without co-payment from the employee or employer, within the larger framework of the national healthcare system by one of the four not-for-profit Health Maintenance Organizations (HMOs) covering the entire civilian population (Rinsky-halivni et al. 2020).

Threshold shifts

The literature demonstrated that the rate of annual hearing deterioration ("annual threshold shift") among noise-exposed workers is approximately 1 dB/year at higher frequencies (Brickner and Carel 2005; Franks 2001; Hetu et al. 1990; Lie et al. 2016; Silva et al. 2022). However, there is measurement variability in audiometric tests as ± 5 dB steps are used to establish hearing thresholds. The margin of error can be notable especially in field conditions where there is lower control of conditions (Barlow et al. 2015). Therefore, the warning value of significant/standard threshold shift (STS) that requires further medical workup and application of control measures is higher than the random audiometric test variation (Dobie 2005; Tikka et al. 2017). Some of the

Table 1 International comparison of hearing surveillance protocols: hearing surveillance frequency and thresholds for further investigation

Country/Region	Hearing surveillance frequency	STS criterion	Reference
Australia	At least every 2 years; employees exposed ≥ 100 $dBL_{Aeq,8\,h}$ may be tested more frequently, e.g., every 6 months	STS has occurred if the monitoring audiogram differs from the reference audiogram in the following way: 20 dB shift at 8000 Hz or 15 dB at 6000 Hz 15 dB shift at 500, 1000, 1500 or 2000 Hz Average threshold shift ≥ 5 dB at 3000, 4000, and 6000 Hz Average threshold shift ≥ 10 dB at 3000 and 4000 Hz	Safe work Australia
Canada Federal:	Not specifically required	Not specified	Occupational health and safety insider (OHSInsider)
British Columbia, Yukon	Baseline test within 6 months and annual tests	Not specified	Occupational health and safety insider (OHSInsider)
Manitoba, Saskatchewan, Northwest Territories and Nunavut	Baseline within 6 months and surveillance every 2 years	Not specified	Occupational health and safety insider (OHSInsider)
Alberta	Annual tests for the first 2 years and surveillance every 2 years thereafter	15 dB at two consecutive frequencies at 1000–6000 Hz compared to baseline	Government of Alberta
European union (EU)	Annual tests	Not specified[a]	Directive 2003/10/EC-noise
Israel	Annual tests	15 dB from a previous examination that exceeds 30 dB hearing level at 1000–4000 Hz	Israel Ministry of Economy and Industry (Labour)
New Zealand	Annual tests	Threshold shift ≥ 15 dB at any frequency when compared with the baseline audiogram	Work-safe New Zealand AS/NZS 1269:1989
South Africa	Annual tests	Average threshold shift ≥ 10 dB at 2000, 3000, and 4000 Hz in one or both ears compared to the baseline audiogram	South African Department of Mineral Resources
Philippines	Not specified	Not specified	Philippines Occupational and health standards (as amended 1989)
Taiwan	Annual tests for workers exposed to ≥ 85 $dBL_{Aeq,8\,h}$	STS has occurred if monitoring audiogram differs from the reference in the following ways: Bilateral, symmetric sensorineural hearing loss Dip in 4000/6000 Hz: hearing loss > 40 dB at 4000 Hz or 6000 Hz, or the hearing loss average at high frequency [(3000 Hz + 4000 Hz + 6000 Hz)/3] is ≧10db than low frequency area [(500 Hz + 1000 Hz + 2000 Hz)/3]	Guidance of Taiwan OSHA and EOM association
United Kingdom	Annual tests for the first 3 years of noise exposure, then at three-yearly intervals	Sum of hearing thresholds at 1000, 2000, 3000, 4000, and 6000 Hz compared to reference tables, stratified by sex and age	British HSE (Health and Safety Executive)
USA:			
OSHA	Annual tests	An average of 10 dB from baseline at 2000, 3000, and 4000 Hz in one or both ears that exceeds 25 dB	US Department of Labor OSHA CFR1904.10

Table 1 (contined)

Country/Region	Hearing surveillance frequency	STS criterion	Reference
NIOSH	Annual tests	15 dB from previous test at any frequency 500-6000 Hz in either ear	US Dept of Health Human Services

dB decibel(s), *dBL*$_{Aeq,8\ h}$ A-weighted equivalent continuous sound over an 8-h period, *Hz* hertz, *NIOSH* National Institute for Occupational Safety and Health, *OSHA* Occupational Safety and Health Administration, *STS* significant or standard threshold shift

[a]A universal protocol for establishing STS in the European Union could not be obtained in the literature, on the EU-OSHA website and in Directive 2003/10

common recommendations regarding the STS criterion, ranging between 10 and 15 dB, are shown in Table 1.

Study aims

The standard annual testing frequency may not reliably detect the annual threshold shift. This study aimed to investigate the annual rate of clinical deterioration of hearing of workers in Israel. Second, the study aimed to propose an effective, efficient, hearing screening frequency protocol for NIHL screening in noise-exposed workers in the context of modern labor markets based on empiric data.

Methods

Study population

Male workers, aged 18 years and above at first audiogram, from workstations certified to be hazardously noisy were eligible for inclusion in the noise-exposed group. Employees in noisy workstations with audiometric records of at least seven checkups and a 1-year gap between examinations were included in the exposed group. Participants met the eligibility criteria for the reference group if they were employed as crane operators, participating in mandatory occupational medical monitoring at a Jerusalem district HMO between 2006 and 2017, not concomitantly exposed to hazardous noise, and had at least four audiometric tests.

Crane operators were selected as a reference group as their workstations are verified to be non-exposed to occupational hazardous noise. Based on previous studies of tower and truck-mounted crane operators, it was assumed that the referent participants were exposed to an average of 76 dBL$_{\text{Aeq,8 h}}$ (Sellappan and Janakiraman 2014). Their operation license requires them to be medically fit through medical monitoring, which includes, inter alia, hearing tests.

Women were excluded since more than 96% of the data available were from male workers. Workers with obvious cases of non-NIHL, e.g., documented chronic conductive HL or history of other causes of hearing impairment and those with profound degree of sensorineural HL at baseline audiogram were excluded. Based on previous studies, a ratio of exposed: non-exposed of approximately 3:1 and a standard deviation of 5 dB were used to estimate sample size for comparing mean threshold shifts between the groups (Lutman et al. 2008).

Data collection and study variables

Data on workers' sociodemographic characteristics (age, gender, ethnicity, rural/urban residential area), occupational variables (industry, years in service hazardous noise-exposure history and duration, noise level of work environment, ototoxic concomitant occupational exposures), information on potential clinical factors known to be correlated with impaired hearing (diabetes, hypertension, smoking status, and medications) (Sliwinska-Kowalska 2020) and consecutive hearing monitoring results were obtained from the electronic medical records (EMRs) of the Jerusalem occupational medicine clinic between 2006 and 2017. Information on noise exposure levels of workstations in the plants where participants were employed was obtained from electronic files of the occupational medicine clinic derived from the Ministry of Labor factories' registry. A certified hygienist assessed noise level, as required by the Israeli law, according to international organization for standardization (ISO9612 standards) using personal monitoring approach sound level meters or noise dosimeters with personal monitoring approach. Mandatory workstation-based noise exposure measurements during the study period were used to assess exposure levels of the exposed group's workplaces.

Baseline and consecutive screening hearing monitoring audiograms in the EMRs were conducted by trained nurses or audiologists, then analyzed by a certified occupational physician who decided on required investigation. Audiometry was performed following American National Standards Institute (ANSI standards) described in supplemental table S1, which includes additional operational definitions. The bilateral mean of 1–4 kHz and 0.5–2 kHz frequencies was used for analyses. Audiograms were omitted if unlikely threshold values with unusual patterns that suggest the presence of testing or patient recognition errors were noted. Confirmatory audiograms repeated within a 9-month period within the same year were averaged out. The North American Industry Classification System (NAICS) was used to classify all workstations into four major service industries, i.e., manufacturing, services, transport and warehousing, and construction industries. Chronic health conditions were recorded both if first diagnosed in the EMRs during follow-up and at baseline as diabetes are often not clinically diagnosed until a decade after onset (Baker et al. 2018; Ohishi 2018).

Data analysis

Data were analyzed with SPSS version 26 (IBM Corp., Armonk, NY). Bivariate analyses of associations between the characteristics of study subjects in the reference and noise-exposed group were evaluated using a Chi-square test. Two-sided tests of significance were used, and statistical significance was set at $P < 0.05$. Data were stratified by age (50 years and above, and below 50 years), given the unbalanced age of exposed and referent group and the association between age and HL. Presbycusis affecting the frequency range tested through occupational pure tone audiometry generally occurs around and after age 50, hence selection of 50 years as the cut-off (Arvin et al. 2013; Lie et al. 2016).

The mean noise exposure (2006–2017) of each of the plants where the noise-exposed participants worked was calculated by averaging the 8-h time-weighted average (TWA) noise doses of all measured workstation in the workplace. Noise exposure measurements from all workstations and factories were first converted to percentage dose as they could not be directly averaged in the logarithmic scale. A dose of 100% is equivalent to the permissible noise exposure (threshold limit value—TLV) of 85 $dBL_{Aeq,8\ h}$ and a 3 dB-exchange rate was used to calculate dose. Noise levels were presented in both noise doses scale and by conversion back to the logarithmic A-weighted scale in decibels.

Mean individual threshold shifts for each worker (1–4 kHz) in time periods of 1 year, 2 years, 3 years, up to 8 year intervals between checkups were calculated simulating different surveillance intervals of each study subject to maximize data usage (see Fig. 1 for schematic diagram). For each worker, pure tone average (PTA) thresholds of the latter year were subtracted from the former year according to desired time interval. For each time interval, all possibilities were then averaged

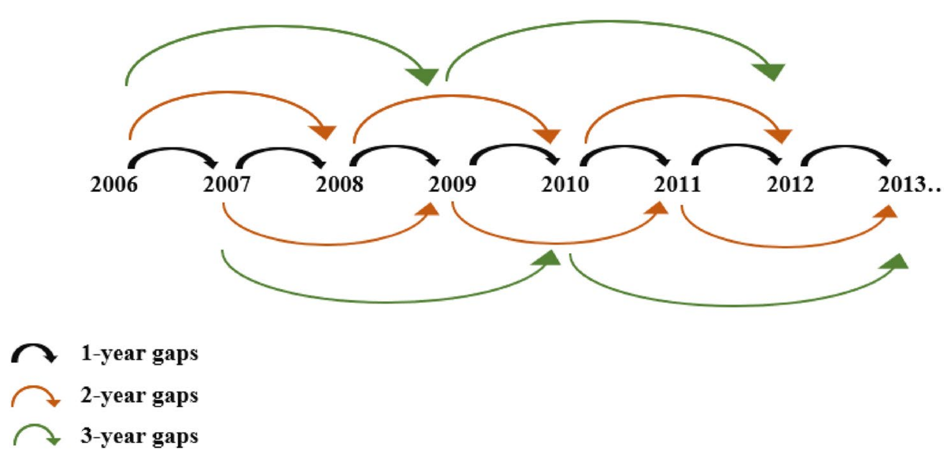

Fig. 1 Calculation method of mean annual thresholds shift (gaps) in different time intervals between checkups

to obtain the personal threshold shift mean. Afterward, the threshold shifts of each given time interval per person were summed together and divided by the number of study subjects and by the interval years to get a mean annual threshold shift (ATS) for each time interval. Standard deviations of the within-person means were calculated across all thresholds shifts of each time interval of every individual. Afterward, based on the within-person means, the between-person standard deviations were computed for the various time intervals. See equation S1 for calculation formulas and examples.

We stratified for years in service by assessing noise-exposed workers (with up to three years) and following them up to 12 years, giving a maximal range of 15 years, which is in accordance with the sparse evidence of accelerated occupational NIHL in the first 10–15 years employment (Kamal et al. 1989). Employees with 0–3 years in service at baseline were compared to those with longer years of exposure.

A Joinpoint regression analysis was used to assess timing of significant magnitude change in trends of mean ATS between increasing audiological checkups intervals, toward a zero slope. It indicates that mean ATS values are similar when calculated between consecutive time intervals, and therefore more accurate. Mean threshold shifts calculated for annual changes, from annual checkup interval up to 8 years, were used to compute the curves and Joinpoints utilizing Monte Carlo method set to 10,000 permutations and considering the existence of autocorrelation (Joinpoint Regression Program version 4.9.1.0, National Cancer Institute, Bethesda, Maryland). For each time interval, we calculated the coefficient of variation (standard deviation divided by the mean) to investigate the relationship between the variability of mean ATS values obtained from the exposed workers when calculated for different time intervals between checkups. A Joinpoint for trend change was then sought to determine the dispersion trend changes along the increasing time intervals for ATS calculations. A flat trend of the slope represents similarity in dispersion of ATS among the noise-exposed participants.

Ethics

This study was approved by the ethics committee of Clalit Health Services. A waiver of informed consent was granted by the committee due the use of anonymous and de-identified retrospective data without access to contact information of participants.

Results

Participant characteristics

A total of 1913 audiograms from 356 male participants (263 noise exposed and 93 reference group of crane operators) were included for analyses. An average of 8.4 and 8 audiograms were obtained per participant (noise exposed and crane operator, respectively) for the 12-year period covering the years 2006–2017.

As shown in Table 2, age distribution was significantly different given that the referent workers, i.e., the crane operators are older in all stratas than the noise exposed. In addition, the proportion of workers belonging to Israel's Arab minority comprised 28% of the noise-exposed group, comparable to the 28.9% share of Arabs among the male workers in Jerusalem district (Israel Central Bureau of Statistics 2011). However, only 17% of crane operators were Arabs. The distribution of enrollment time, smoking status, residential area, diabetes, and ototoxic exposures was similar between the two groups. Age and hypertension are highly associated, hence the likely explanation for the significant difference in the distribution of hypertension with the reference group (older) having higher incidence (Lie et al. 2016). Distribution of ototoxic drugs, parallel exposure to chemicals were assessed; however, the number of study subjects in the groups was too small for further analyses.

Table 3 shows hearing screening status at baseline, or on first computerized follow-up in 2006. Across all variables, the exposed group of workers showed a trend of higher percentages with hearing impairment compared to the crane operators, especially among oldest and longest serving subcategories. Hearing status distribution by ethnicity at baseline showed significant differences between Jews and Arabs, with Jews having higher HL percentages in both referent and exposed groups, explained by the relative older age of Jewish workers ($P < 0.001$, data not shown).

Noise level exposure during the research period

Noise-exposed participants worked in plants with a mean of 91.6 $dBL_{Aeq,8\,h}$ (459% dose), 5% trimmed mean of 90.3 $dBL_{Aeq,8\,h}$ (340%), median of 88.6 $dBL_{Aeq,8\,h}$ (230%) for the period relevant to the study (IQR 85.4–91.4 $dBL_{Aeq,8\,h}$) (supplemental figure S1). In total, 9.4% of the factories had mean noise levels above 95 $dBL_{Aeq,8\,h}$ (1000% dose), while 12.5% were within the acceptable exposure limit of 85 $dBL_{Aeq,8\,h}$ (up to 100% dose).

Annual threshold shifts stratified by age

Given the significant differences in age distribution of exposed and referent groups, stratification by age was conducted (Table 4). Joinpoint among the younger than 50, exposed group (Fig. 2), located at mean ATS calculated in 4-year interval demonstrates significant changes in the slope ($P = 0.01$) that was moderated toward zero as checkup intervals increased. Among the reference group, an ATS trend change was evident when calculated

Table 2 Characteristics of participants exposed and referent groups at baseline

Variable	Sub-categories	Exposed group		Reference group		*P value
		n	%	n	%	
Gender	Male	263	100	93	100	
Age (years)	< 35	53	20.2	16	17.2	0.002
	35–50	121	46	27	29	
	50 +	89	33.8	50	53.8	
Year of entry into cohort	2006	178	67.7	60	64.5	0.385
	2007	46	17.5	22	23.7	
	2008–11	39	14.8	11	11.8	
Years in service	0–3	50	19	12	12.9	0.041
	4–10	56	21.3	15	16.1	
	11–20	78	29.7	23	24.7	
	21 +	79	30	43	46.2	
Industry type (NAICS)	Manufacturing	144	55	10	10.8	< 0.001
	Services	85	32.4	5	5.4	
	Construction	18	6.9	72	77.4	
	Transport and warehousing	15	5.7	6	6.5	
Smoking status	Never smoked	98	41.9	43	46.7	0.425
	Ex/current-smoker	136	58.1	49	53.3	
	Missing	29		1		
Ethnicity	Arab	67	25.5	14	15.1	0.039
	Jew	196	74.5	79	84.9	
Area of residency	Urban	221	84	80	86	0.648
	Rural	42	16	13	14	
Hypertension	No	184	70	51	54.8	0.008
	Yes	79	30	42	45.2	
Diabetes	No	219	83.3	78	83.9	0.893
	Yes	44	16.7	15	16.1	
Ototoxic medications and concomitant exposure[a]	No	259	98.5	89	95.7	0.12
	Yes	4	1.5	4	4.3	

NAICS North American Industry Classification System

**P* value from Pearson Chi-square test excluding missing values, Fisher's exact test *P* value for small samples where Expected < 5. *P* value for testing differences in the baseline distributions of characteristics between the noise exposed and referent groups at baseline

[a]Concomitant exposure included lead and halogenated solvents such as industrial trichloroethylene (TCE)

at 3-year intervals onward. Mean ATS stabilized around 0.83 dB from 4-year test intervals among the exposed, slightly higher than the steady 0.65 dB in the reference group obtained from triennial interval and onward.

As opposed to the younger workers, a significant clear Joinpoint (homogenous hearing deterioration trend) was not obtained when ATS were calculated using consecutive multi-annual checkup intervals among noise-exposed workers aged 50 and above (Figure S2). Their annual hearing deterioration means oscillate around an ATS of about 1.15 dB (Table 4). In addition, the Joinpoint analysis in the older reference group demonstrated less stability in threshold shift trend along the sequential time intervals compared to younger crane operators. Therefore, further analyses were performed on the younger age group of below 50 years.

Figure 2 and Figure S2 demonstrate consistent pattern in the directions of the deviation from steady values in ATS obtained from higher test frequencies (annual and biennial): deviation toward higher average ATS in the exposed group and lower in the reference group.

Variability of annual change when calculating ATS in different hearing screening intervals

Figure 3 demonstrates that as the time interval between consecutive hearing checkups increased, the mean annual change (ATS) variability decreased, implying on improved

Table 3 Baseline hearing screening status

Variable	Sub-categories	Exposed group				Reference group				*P value
		Hearing status				Hearing status				
		Normal		Mild-mod HL		Normal		Mild-mod HL		
		n	%	n	%	n	%	n	%	
Age	< 35	48	90.6	5	9.4	16	100	0	0	< 0.001
	35–49	103	85.1	18	14.9	27	100	0	0	
Years in service	50+	51	57.3	38	42.7	39	78	11	22	
	0–3	43	86	7	14	12	100	0	0	0.025
	4–10	48	85.7	8	14.3	15	100	0	0	
	11–20	62	79.5	16	20.5	21	91.3	2	8.7	
	21+	47	59.5	32	40.5	33	76.7	10	23.3	
Industry type (NAICS)	Manufacturing	105	72.9	39	27.1	10	100	0	0	0.024
	Services	70	82.4	15	17.6	5	100	0	0	
	Transport and warehousing	10	66.7	5	33.3	6	100	0	0	
	Construction	14	77.8	4	22.2	60	83.3	12	16.7	
Ethnicity	Arab	54	80.6	13	19.4	13	92.9	1	7.1	0.036
	Jew	146	74.5	50	25.5	68	86.1	11	13.9	

NAICS North American Industry Classification System of 2017, *HL* hearing loss, *Mild-mod HL* mild to moderate hearing loss at baseline

*Pearson Chi-square *P* value comparing hearing screening status at baseline or on first computerized follow-up in 2006 across variables between the noise-exposed group and the referent group of workers

Table 4 Threshold shifts (1–4 kHz average) in exposed and referent group calculated according to time intervals of checkups stratified by age below 50 years and 50 years and above

Age	Time intervals between checkups (years)	Exposed group			Reference group		
		n	Mean per year (dB)	SD	n	Mean per year (dB)	SD
< 50 years	1	174	1.1	5.93	28	0.11	8.36
	2	174	0.99	3.21	43	0.58	3.35
	3	174	0.94	2.18	31	0.74	2.86
	4	174	0.84	1.56	41	0.69	1.62
	5	174	0.83	1.16	31	0.65	1.84
	6	172	0.83	1.01	37	0.66	0.82
	7	160	0.87	0.76	28	0.62	0.62
	8	145	0.83	0.61	28	0.54	0.5
≥ 50 years	1	89	1.28	7.28	50	0.85	6.69
	2	89	1.04	3.61	49	0.99	3.64
	3	89	1.07	2.59	49	0.97	2.61
	4	89	1.21	1.88	49	1.11	1.84
	5	89	1.15	1.39	49	1.18	1.44
	6	89	1.09	1.26	44	1.14	1.13
	7	85	1.14	0.93	41	1.04	0.97
	8	77	1.14	0.93	39	0.95	0.64

dB decibel(s), *SD* standard deviation

accuracy. The moderation of the slope is seen from triennial interval onward. The mean coefficient of variation decreased from 5.39 (95% CI [4.82, 5.96]) for annual interval to 2.3 (95% CI [2.07–2.57])—a decrease in 58% for triennial interval. A Joinpoint located at 3-year interval with reduction in slope at lower test frequencies signifies the checkup frequency in which the variability decreases most substantially.

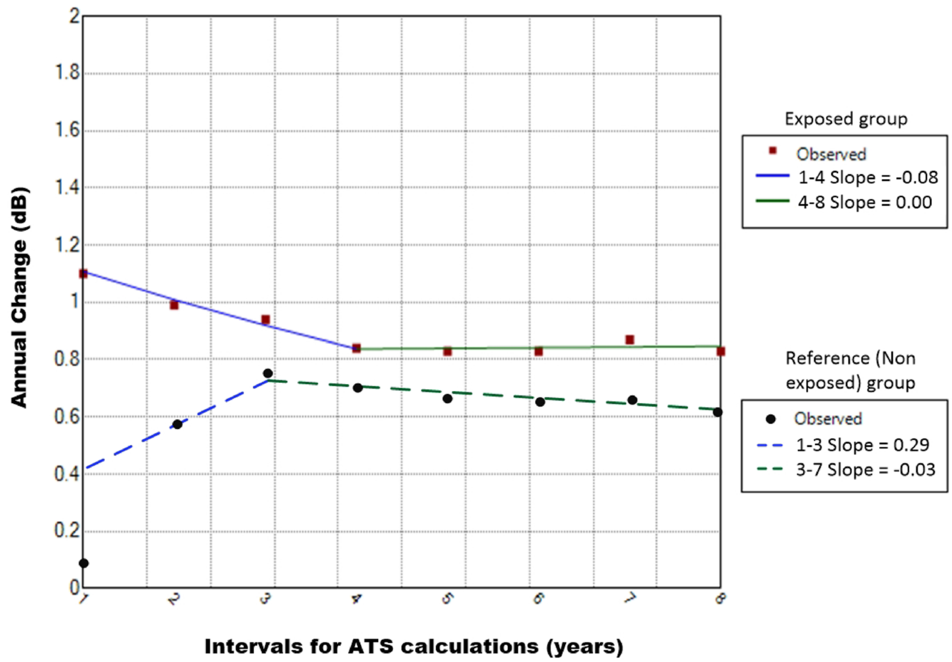

Fig. 2 Joinpoint trend analyses of mean annual threshold shifts among exposed (rectangles) and reference groups (circles and dashed trend lines) calculated according to consecutive time intervals of hearing checkups for participants aged below 50 years at entry

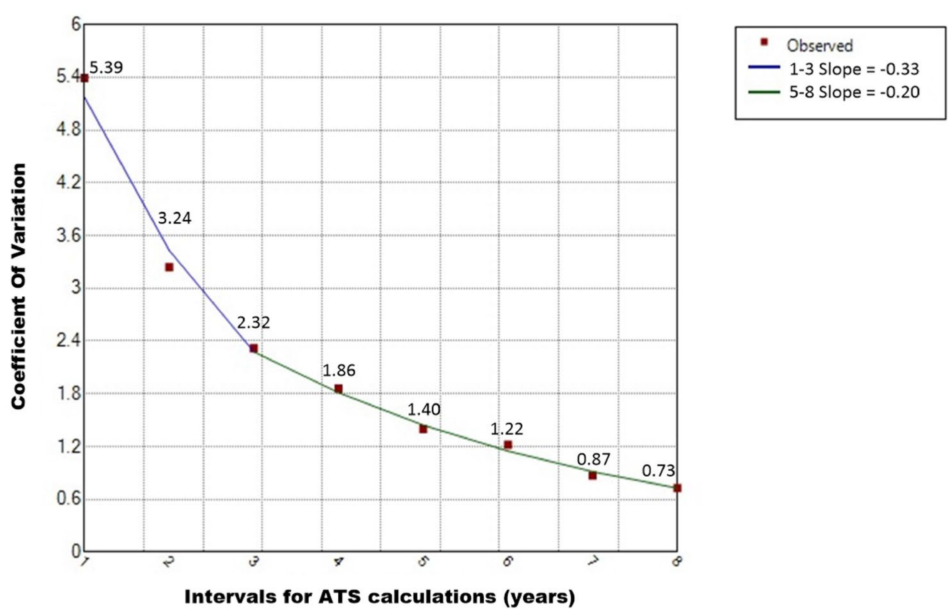

Fig. 3 Joinpoint trend analyses of annual threshold shifts variability, represented by coefficient of variation (standard deviation divided by mean) according to sequential time intervals for calculating ATS among noise-exposed workers aged below 50 years at entry. As the time interval between consecutive hearing checkups increased, the mean annual change (ATS) variability decreased, implying improved accuracy

Annual threshold shifts stratified by duration of employment

To evaluate the noise-induced deterioration rate among newly exposed workers, further analysis of hearing threshold shift by years in service at entry was performed among noise-exposed workers below age 50 (Fig. 4). On average, the newly exposed group was 5 years younger relative to the more senior (33 versus 38, respectively). The comparison showed no significant differences at any time interval among participants with up to 3 years of exposure at baseline compared to the more senior workers and no accelerated NIHL among newer workers was demonstrated ($P > 0.05$ at all intervals between checkups, data not shown).

Discussion

According to our review, in Israel as well as in many other countries, it is customary to perform annual audiometric screening of noise-exposed workers and compare annual audiometry tests with the previous tests to calculate an ATS.

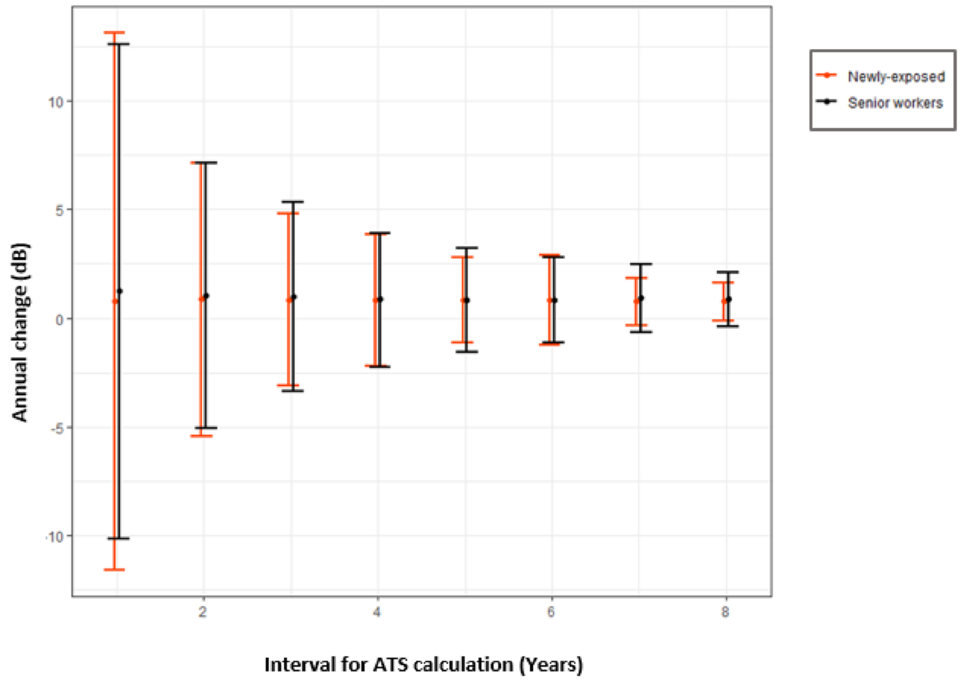

Fig. 4 Mean annual threshold shifts calculated according to consecutive time intervals of hearing checkups in noise-exposed workers aged below 50 years at entry: newly exposed who had 0–3 years of service at baseline ($N=47$), compared to senior workers who had more than 3 years of exposure at baseline ($N=127$). Abbreviations: dB, decibel(s); ATS, annual threshold shifts. All *T* tests between newly exposed and veteran workers were non-significant ($P>0.05$)

Given the 5 dB margin of error when performing hearing tests and the slow rate of NIHL, threshold shift between annual audiometry tests might miss a real significant shift (STS) over a longer period or alternatively may produce an artifactual annual change leading to unnecessary medical investigations. This pioneering follow-up study, using Joinpoint of threshold shift means and variability of different intervals of hearing screening for the first time, assessed the accurate annual rate of occupational NIHL and the frequency of follow-up required to detect HL when comparing a test to its predecessor.

1–4 kHz rate of annual decline stratified by age and years in service

Our findings revealed that among the noise-exposed workers, using the 1–4 kHz average, the threshold shifts stabilized from 3 years onwards at around 1 dB per year in all age groups and 0.83 dB in the stratum younger than 50 years. The annual deterioration rate of 1 dB resembles previous studies (Brickner and Carel 2005; Hetu et al. 1990; Lie et al. 2016; Silva et al. 2022). For the reference group, age stratification demonstrated an annual hearing threshold shift at 3-year intervals onwards, stabilized at 0.65 dB among younger workers aged below 50. Nevertheless, we could not characterize a clear trend of stabilization of the ATS along the multi-annual test intervals within the older exposed and reference sub-groups aged 50 and above. The instability of the threshold shift averages is probably due to the strong non-linear age effect on HL. However, we were able to estimate the average annual HL value among the exposed workers at 1.15 dB.

Another critical element was to assess threshold shifts in the first years of exposure according to evidence in the literature, based on ISO 1999:1990 (International Organization for Standardization) nomograms or unprotected excessive noise exposure levels, for accelerated rate of HL, which might necessitate more frequent surveillance in the early post-exposure period (International Organization for Standardization 1990; Kamal et al. 1989; Keatinge and Laner 1958; Lie et al. 2016). In the UK and in some provinces of Canada, annual hearing tests are conducted in the first years of employment followed by a bi-/triennial surveillance (EU-OSHA 2005; Government of Alberta 2017; OHS Insider 2021). Our results, however, did not support an enhanced decline in the first years of service compared with those later years of exposure. An explanation for this difference could be that new workers are effectively using personal protective equipment, and are aware of the risk of hazardous noise and are younger.

Our findings corresponded with the evidence that the 10 years of exposure to a daily average of 85–90 $dBL_{Aeq,8\ h}$ results in an average threshold shift of 4–9 dB at 1–4 kHz and first 5 years with 3 dB (Lie et al. 2016; Silva et al. 2022).

Hearing loss in modern labor market settings

The study results revealed that annual hearing threshold shifts are higher in the noise-exposed group of workers as compared to the reference group despite mandatory use of hearing protection equipment, and improved engineering control measures in the last decades which led to relatively low (median of 88.6 $dBL_{Aeq,8\ h}$) exposure levels in factories in the Jerusalem district. The findings suggest that the currently legislated hearing conservation practices and monitoring systems are imperfect in preventing NIHL, which remains the leading occupational disease reported to the registry in Israel. Consequently, further strategies are required to improve risk control among the numerous workers exposed to hazardously noisy occupational settings.

Surveillance frequency

The degree of change expected between tests annually is much smaller than the existing variability due to test conditions and hearing testing techniques of ± 5 dB steps, as reflected by the large coefficient of variation and weighted annual standard deviations in both exposed and reference groups. This is more pronounced among the noise-exposed workers, whose hearing testing is frequently conducted in the factory area, by different examiners and not always after the recommended noise-exposure avoidance time, that can result in the transient temporary threshold shift (TTS) (Codling and Fox 2013). As per our findings, threshold shifts calculated using testing intervals of 1 and 2 years are unreliable given the tendency for a positive error in exposed groups, and negative error in non-exposed groups. In effect, hearing threshold shifts calculated at intervals of at least 3 years reflect more accurately the exact annual decline rate of the employee. Reduced measurement error when calculating annual rate of deterioration over longer intervals between hearing tests might explain the stabilization in mean ATS values. Nevertheless, findings are less clear regarding older workers, strongly influenced by the non-linear rate of deterioration due to age. Researchers have not yet succeeded in finding an age correction mechanism for workers over the age of 60 to obtain the real rate of hearing deterioration due to noise exposure (Dobie and Wojcik 2015). In practice, the OSHA correction is only until age 60 (Dobie and Wojcik 2015).

An annual testing frequency is costly in terms of money, resources, and time of the health system, employees and employers, potentially reducing compliance (Windapo 2013). Therefore, there is a need to balance measurement accuracy with compliance and the risk of missing STS, signifying potential NIHL that needs to be adressed to protect workers' health.

Given the issues highlighted in our study concerning annual screening, the triennial method whereby hearing tests are conducted at 3-year intervals is recommended unless workers are of older age, or a hearing problem or accelerated HL is detected. A similar protocol is currently adopted by the British HSE, though we were not able to discern the evidence base of this practice. However, our findings did not support frequent surveillance in the initial years of employment as the HSE protocol (Codling and Fox 2013). The average expected annual change of 0.8 dB, as we observed among noise-exposed workers younger than age 50, suggests that the intervals between each subsequent test should be considered so as to identify a significant and real deterioration in hearing. In this way, unnecessary medical investigations and unjustified displacement of employees from work to comply with legislation can be avoided. The South African regulations use the baseline audiogram obtained at the start of a worker's work life as the reference to which all future periodic audiograms are evaluated (Grobler et al. 2020). Continuously referring to the baseline audiogram (which is periodically revised after a STS), together with spaced assessments, could improve accuracy and effectiveness of hearing assessments.

Other considerations such as risk factors for HL and primarily age of workers should be factored in (Codling and Fox 2013; Themann and Masterson 2019) and further studied in relation to desired screening frequency. However, for the average healthy worker, there is no additional benefit in conducting annual tests over triennial tests. Since frequent surveillance is recommended for highly exposed workers in some countries (e.g., safe work Australia for exposure greater than 100 $dBL_{Aeq,8\ h}$), we recommend on lower surveillance frequency to be performed for those who are exposed to relatively lower noise levels (Franks 2001; Safe Work Australia 2018).

Strengths and limitations

To the best of our knowledge, no previous studies have examined the rate of occupational NIHL using different time intervals to establish an evidence-based hearing screening frequency protocol for different noise-exposed strata. Additionally, the computerized dataset enabled the use of comprehensive data which included a wide range of demographic, clinical, and occupational parameters compared to subjective questionnaires frequently used in occupational surveillance. The universal occupational medicine services in Israel (free of co-pay) allow research to include workers from all noise-exposed work sectors. Furthermore, the record-keeping practice enables inclusion in the dataset of many repeat investigations for each worker with the same instruments and test operators, enabling accurate calculations of average threshold shifts. Selection of workers with multiple checkups minimized the risk of attrition. In addition, the calculated simulation of different surveillance intervals allowed optimal use of the available data. Referral of all noise-exposed workers for hearing conservation surveillance is mandated by law and not subject the discretion of the workers or the employer, thereby minimizing bias. This is a "real life" cohort; therefore, practical recommendations can be drawn from the study.

Limitations include the lack of data regarding prior exposure to noise among crane workers who may have held other job titles in the construction industry before becoming crane operators; however, we screened all participants at baseline for severe-profound HL. In addition, exposure misclassification by employers (who may classify an unexposed worker as exposed and refer for hearing monitoring or a crane operator who works in parallel with exposure to noise, not referred for monitoring), cannot be ruled out. We were limited by a small sample size in the reference group since non-exposed workers are not regularly screened for HL. Moreover, less stringent measures on hearing screening frequency in the reference group of crane operators resulted in missing tests. The reference group although older, might introduce a "healthy worker effect" bias, including better hearing since it is a part of their fitness for duty requirements (Chowdhury et al. 2017). We, therefore, expected the workers in the reference group to be more incentivized to demonstrate better results of hearing tests. In contrast, noise-exposed workers might make lesser effort due to a possible secondary gain motive for work injury compensation. Nevertheless, average of threshold shifts along wider intervals may reduce effects of worker effort, and this may sharpen the difference in threshold shifts between the two groups. Moreover, it is possible that some exposed workers were not tested in ideal conditions (in the factory, sometimes exposed recently). In addition, we could not obtain the specific exposure status of each worker but rather used the factories mean to get a notion on the general noise exposure level of the workers in the cohort. Better characterization of the individual noise level would enable better tailoring surveillance recommendations. We excluded women from our study due to small numbers. Previous studies demonstrated higher susceptibility among males to noise-induced hearing shifts. However, our findings were comparable with studies where participants were of both sexes possibly due to most studies reporting higher proportions of male employees in the noisy industries (Lie et al. 2016). Further studies are needed to include occupationally noise-exposed women.

In conclusion, this study for the first time provides evidence for the accuracy of annual hearing threshold shifts of noise-exposed workers when calculated at 3-year interval onwards. The accurate ATS is at about 0.8 dB shift annually among workers below 50 years in the context of modern industry. Margins of errors of the test method are much larger than the ATS found, thus requiring a screening schedule that enables each subsequent test to identify a significant and real deterioration in hearing. Worse than that—missing a gradual deterioration that would not be revealed by annual testing, especially if the comparison is with the previous annual test. In practice, for the relatively low category of noise-exposed workers (85–92 $dBL_{Aeq,8\,h}$) as in Jerusalem district in Israel, a triennial audiometric screening frequency method would be a clinically feasible surveillance method for workers without other known risk factors and enhance compliance.

Further studies are recommended to replicate the findings using a larger sample size and different strata of noise exposures investigating female and Arab minority workers as well as participants with additional risk factors for HL. As a first step, and pilot research, it is advisable to consider calculating 3-year intervals of each exposed worker attending the traditional annual hearing surveillance to enhance informed decision-making for screening. Moreover, it is worthwhile to add, to the screening policy, the use of long-term averages of threshold shifts for each worker not to miss STS, instead of using threshold shifts between adjacent checkups, as customary in Israel and other countries.

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Author contributions NM, OP, MK, and LRH participated in the conception and design of the study. NM and LRH participated in the acquisition of data, performed the analyses and interpretation of data, and drafted the article. All authors contributed to the further interpretation of data, revising the manuscript critically for important intellectual content and final approval of the version to be submitted.

Data availability The data that support the findings of this study are available from Clalit Health Services, but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are, however, available from the authors upon reasonable request and with permission of Clalit Health Services.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

Ethical approval and informed consent The study was approved by the ethics committee of Clalit Health Services, Israel. A waiver of informed consent was granted by the committee due to the use of anonymous and de-identified retrospective data without access to the contact information of participants.

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