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Noise-Induced Hearing Loss – A Preventable Disease? Results of a 10-Year Longitudinal Study of Workers Exposed to Occupational Noise

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Abstract

Aims: To survey current, Danish industrial noise levels and the use of hearing protection devices (HPD) over a 10-year period and to characterise the association between occupational noise and hearing threshold shift in the same period. Furthermore, the risk of hearing loss among the baseline and the follow-up populations according to first year of occupational noise exposure is evaluated. **Materials and Methods:** In 2001–2003, we conducted a baseline survey of noise- and hearing-related disorders in 11 industries with suspected high noise levels. In 2009–2010, we were able to follow up on 271 out of the 554 baseline workers (49%). Mean noise levels per industry and self-reported HPD use are described at baseline and follow-up. The association between cumulative occupational noise exposure and hearing threshold shift over the 10-year period was assessed using linear regression, and the risk of hearing loss according to year of first occupational noise exposure was evaluated with logistic regression. **Results:** Over the 10-year period, mean noise levels declined from 83.9 dB(A) to 82.8 dB(A), and for workers exposed >85 dB(A), the use of HPD increased from 70.1 to 76.1%. We found a weak, statistically insignificant, inverse association between higher ambient cumulative noise exposure and poorer hearing (−0.10 dB hearing threshold shift per dB-year (95% confidence interval (CI): −0.36; 0.16)). The risk of hearing loss seemed to increase with earlier first year of noise exposure, but odds ratios were only statistically significant among baseline participants with first exposure before the 1980s (odds ratio: 1.90, 95% CI: 1.11; 3.22). **Conclusions:** We observed declining industrial noise levels, increased use of HPD and no significant impact on hearing thresholds from current ambient industrial noise levels, which indicated a successful implementation of Danish hearing conservation programs.

Keywords: Hearing conservation, noise exposure assessment, noise-induced hearing loss, noise surveillance, occupational noise exposure

INTRODUCTION

Occupational noise exposure is recognised as a substantial risk factor for hearing loss, and worldwide, it remains the most frequent cause of preventable sensorineural hearing loss.^[1,2] This has led to an extensive research into the auditive effects of occupational noise, and in consequence, preventive measures have been implemented. These include engineering solutions minimising noise emission and reflection, and legislations limiting the time of work-related noise exposure and obliging the use of hearing protection devices (HPD).^[3-5]

This means that industrial noise levels and individual occupational noise exposure have potentially changed over the last few decades, at least in the developed countries. There are, therefore, good reasons to continue assessing the burden of auditive disease from occupational

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noise at national or sub-national levels to follow up on the possible effect of preventive initiatives. A recent systematic review on occupational noise exposure and hearing concluded that hearing loss due to workplace noise was a significant problem in the 1960s and 1970s in industrialised countries, but the impact seemed to have decreased since that period.^[6] This was suggested to be due to preventive measures, improved regulation or decreased noise exposure. The evidence, however, was still limited mainly due to blunt or incomplete exposure data. Hearing data were concluded to be generally good. Results from other recent studies, also seem to differ between industries, and these studies are often based on one specific profession, limiting generalisation of results.^[7-9]

On the basis of the cross-sectional data collected in 2001–2003, we found a three-fold increased risk of hearing handicap among the workers with first exposure to occupational noise before the 1980s.^[10] However, the workers starting their work in a noisy environment during later years showed no increased risk. We interpreted these findings as the result of successful preventive programmes enforced during 1980–1990. To follow up on these results, we conducted an equivalent survey in 2009–2010.

The main objectives of this study were to describe the trends in industrial noise exposure levels and use of HPD over a 10-year period. Furthermore, we aimed to evaluate the association between current, Danish industrial noise levels and hearing threshold shift in the same period and analyse whether year of first occupational noise exposure was associated with hearing loss.

MATERIALS AND METHODS

Participants

This study has taken advantage of an initial survey of 819 workers conducted between 2001 and 2003 in Aarhus, Denmark, with the purpose of monitoring occupational noise exposure, auditory function and preventive measures (use of hearing HPD) among noise-exposed workers. Participants were recruited from randomly selected companies within 12 trades: children day care (due to reports indicating high noise levels in these units), financial services (expected to have low-level noise exposure) and the 10 manufacturing trades in Denmark with the highest reporting of noise-induced hearing loss according to the Danish Working Environment Authority. In 2009–2010, the same companies and workers were asked to participate again. We were able to re-identify 756 participants. Owing to time and economic restraints, 202 participants (27%) were not contacted (at random) leaving 554 eligible for follow-up. A total of 271 workers (49%) responded and agreed to participate again. At follow-up, 394 workers within the 12 trades were recruited *de novo* to include new workers first to have

been noise-exposed during later years, making a total of 665 participants in the follow-up cohort.

For cross-sectional analysis of the baseline population, we excluded 76 workers with incomplete questionnaire exposure information or no noise dosimetry, 16 workers with incomplete audiometry, 109 white-collar workers (typically managers and office workers considered to differ considerably from the remaining population with respect to extraneous predictors of hearing loss), 65 workers reporting current or prior chronic middle-ear infection or tympanic membrane perforation (possible conductive hearing loss) and finally 14 workers with asymmetrical hearing loss (possible hearing loss from other causes than noise, as defined in section 'Audiometric measures'), resulting in 539 eligible workers for baseline cross-sectional analysis.

Correspondingly, for cross-sectional analyses on the follow-up population, we excluded 38 workers with incomplete questionnaire exposure information or no noise-dosimetry, 98 white-collar workers, 75 workers reporting current or prior chronic middle-ear infection or tympanic membrane perforation and 30 workers with asymmetrical hearing loss, resulting in 424 eligible workers.

For the longitudinal analyses, we focused on the 271 workers participating in both surveys. Of these, 262 had complete audiometries from both surveys. We excluded two workers with incomplete questionnaire exposure information, 48 white-collar workers and the workers reporting either chronic middle ear infection ($n=2$), tympanic membrane perforation ($n=2$), skull fracture ($n=0$) concussion ($n=1$), meningitis ($n=0$) or Meniere's disease ($n=0$) in the follow-up period, resulting in a final study population of 207 persons.

The local ethical scientific committee approved the study (M.20080239). All the participants gave written, informed consent to participate.

Audiometric measures

Air-conduction thresholds were determined for each ear at 0.25, 0.5, 1, 2, 3, 4, 6 and 8 kHz by pure-tone audiometry at the workplaces, using a Voyager 522 audiometer equipped with TDH-39 headphones (Madsen Electronics, Taastrup, Denmark). The audiometer was installed in a mobile examination unit equipped with a soundproof booth (model AB-4240, Eckel Noise Control Technologies, Bagshot, UK). Audiometry was performed by trained examiners using a standardised protocol (according to ISO 8253-1:2010).

To avoid the temporary threshold shifts (TTS) from possible noise sources, all participants were asked to wear HPD from the beginning of the workday until the audiometry was performed. The majority of the workers were daytime workers (around 90% in both surveys), and we expected a limited noise exposure prior to starting the work (mostly night time noise at home) and thus limited

risk of TTS. Otoscopy verified that ears were free of wax, and the tympanic membrane was visible. The audiometer was calibrated every six months according to ISO 389-1:1998. On the basis of pure-tone air-conduction thresholds, we calculated an average binaural hearing threshold level for the critically noise-sensitive frequencies at baseline and follow-up (3–6 kHz-HTL-BL or 3–6 kHz-HTL-FU). Correspondingly, a baseline hearing loss variable and a follow-up hearing loss variable (3–6 kHz-HL-BL and 3–6 kHz-HL-FU) were defined, if 3–6 kHz-HTL-BL or 3–6 kHz-HTL-FU was above 20 dB. Threshold shift from baseline to follow-up (Δ 3–6 kHz-HTL) was calculated by subtracting the baseline hearing thresholds (3–6 kHz-HTL-BL) from the follow-up hearing thresholds (3–6 kHz-HTL-FU). Thus, the worsened hearing was reflected by a positive threshold shift. We regarded an inter-aural difference of 20 dBHL or more in two consecutive frequencies from 3 to 6 kHz as an asymmetrical hearing loss.

Questionnaire information

All participants filled in a questionnaire providing information on medical and professional history. For the purpose of this study, information on age, sex, professional history (current and prior employment, duration, industry, occupation (blue vs. white collar)), use of HPD and the workers judgement (whether noise levels in prior jobs were higher, comparable or lower) was retrieved.

Occupational noise exposure assessment

At baseline and follow-up, individual dosimeters (Bruel & Kjr, model 4443, Naerum, Denmark) measuring A-weighted equivalent sound levels (L_{Aeq}) in 5-second intervals during the full work shift were handed out to the participants. Microphones were fitted at the right side collar if they were right-handers and vice versa if left-handers. Measuring range was set at 70–120 dB(A). Individual A-weighted equivalent noise levels were computed for the full work shift ($L_{Aeq,work}$).

Subsequently, workplace and trade-specific mean noise levels were calculated based on the individual dosimetries. As noise levels were expected to vary more from day to day for the individual worker than between the different workers,^[11,12] we estimated the most efficient grouping strategy based on the highest contrast in mean exposure level between the groups. This was accomplished by modelling the noise exposure with two mixed effect models including either worker and the industry or worker and company as random effects. The highest contrast was found using company-means, and thus worker's noise exposure was classified by the mean L_{Aeq} -value calculated for their workplace and not by her/his individual measurement.

The estimation of cumulative occupational noise exposure in the follow-up period was based on (1) the questionnaire

information on current and previous employment details including company, period, and the workers' subjective judgement of whether any previous jobs involved comparable or higher noise exposure levels than their current job, and (2) workplace average L_{Aeq} levels at baseline and follow-up. Each individual employment year was given a noise exposure level based on the following criteria: (1) if the year was within an employment period in a company included in the study, the average workplace level was applied (2) for employment periods in companies not included in the study, the noise exposure was classified from the participants' judgement of the noise levels, that is, (a) if the worker reported that the noise levels in a prior job were comparable to or higher than the level of the current job (where noise measurements were performed), these years were given the same level as in the current workplace or (b) if the noise level was judged to be substantially lower than that of the exposure at the current company, then this employment period would be classified as non-exposed.

Finally, we calculated cumulative occupational noise exposure levels for each participant in the follow-up period as the product of estimated noise exposure level (L_{Aeq} in dB(A)) and the duration of employment (T) using the formula: $10 \times \log [(10^{dB(A)/10} \times T)]$, resulting in 'dB(A)-year' on a logarithmic scale.

The same model was used to estimate the first year of occupational noise exposure >80 dB(A) and the number of years exposed to the mean occupational noise levels >80 dB (A) and >85 dB(A), respectively.

Statistics

We tabulated sex, age and industry across decade of first year of an occupational noise exposure above 80 dB(A) for the baseline and follow-up populations [Table 1]. For the workers who participated in both surveys, we tabulated sex, age, 3–6 kHz-HL-BL, occupational noise exposure before baseline and HPD use across three categories of cumulative occupational noise in the follow-up period [Table 2].

Logistic regression was used to estimate the association between first year of occupational noise exposure >80 dB (A) and hearing loss in the critically noise-sensitive frequencies for the baseline and the follow-up populations, adjusting for age and sex [Table 3].

Among the workers participating in both the surveys, the crude and the adjusted associations between noise exposure variables and hearing threshold shift in the follow-up period were examined, using the linear regression with the lowest exposure group as a reference [Table 4]. Outcome variables as well as residuals were assessed and found normally distributed. Stratified analyses were performed to evaluate the possible effect modification from a prior occupational noise exposure and baseline hearing

Table 1: Characteristics of 539 workers from the baseline population and 424 workers from the follow-up population by year of first occupational noise exposure >80 dB(A), Aarhus, Denmark

	Baseline population						Follow-up population							
	Year of first noise exposure			<1980			Year of first noise exposure			1980-1989				
	1990-1999	1980-1989	<1980	2000-2010	1990-1999	1980-1989	1990-1999	1980-1989	<1980	2000-2010	1990-1999	1980-1989	<1980	
n	%	n	%	n	%	n	%	n	%	n	%	n	%	
Sex, no. (%)														
Women	52	19.5	22	15.1	14	11.1	29	29.9	38	25.7	20	19.2	10	13.3
Men	215	80.5	124	84.9	112	88.9	68	70.1	110	74.3	84	80.8	65	86.7
Age (years), mean (SD)	267	38.1 (9.4)	146	36.9 (7.0)	126	47.1 (7.0)	97	34.6 (10.0)	148	42.6 (9.2)	104	45.0 (6.1)	75	54.8 (5.5)
Industry (NACE-codes)														
Manufacture of food (15)	33	12.4	19	13.1	18	14.3	20	20.6	16	10.8	14	13.5	5	6.7
Manufacture of wood products (20)	38	14.2	13	9.0	16	12.7	9	9.3	12	8.1	8	7.8	6	8.0
Publishing and printing (22)	33	12.4	25	17.2	16	12.7	8	8.3	17	11.5	9	8.7	7	9.3
Manufacture of non-metallic mineral prod. (26)	25	9.4	12	8.3	15	11.9	7	7.2	7	4.7	5	4.8	7	9.3
Manufacture of basic metals (27)	16	6.0	8	5.5	8	6.4	4	4.1	12	8.1	12	11.5	6	8.0
Manufacture of fabricated metals (28)	34	12.7	21	14.5	17	13.5	11	11.3	24	16.2	13	12.5	8	10.7
Manufacture of machinery (29)	25	9.4	16	11.0	10	7.9	11	11.3	11	7.4	12	11.5	11	14.7
Manufacture of motor vehicles (34)	25	9.4	16	11.0	13	10.3	8	8.3	12	8.1	8	7.7	6	8.0
Manufacture of furniture (36)	7	2.6	6	4.1	4	3.2	1	1.0	2	1.4	2	1.9	0	0.0
Construction (45)	14	5.2	7	4.8	5	4.0	2	2.1	7	4.7	5	4.8	2	2.7
Day care (85)	17	6.4	2	1.4	4	3.2	16	16.5	16	10.8	8	7.7	4	5.3
Other industries	-	-	-	-	-	-	0	0.0	5	3.4	6	5.8	4	5.3
Retired or unemployed	-	-	-	-	-	-	0	0.0	7	4.7	2	1.9	9	12.0

Table 2: Characteristics of the 207 workers participating at both baseline and follow-up by tertiles of cumulative occupational noise exposure (dB(A)-years) in the follow-up period, Aarhus, Denmark, 2009

	Cumulative occupational noise exposure (dB(A)-years)					
	67.7–91.8		91.9– 94.6		94.7–107.0	
	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%
Sex, no. (%)						
Women	21	45.7	11	13.9	13	15.9
Men	25	54.4	68	86.1	69	84.2
3–6 kHz-HL-BL*						
No	33	71.7	51	64.6	56	68.3
Yes	13	28.3	28	35.4	26	31.7
Duration of daily occupational noise exposure > 80 dB(A) before baseline						
<10 years	24	52.2	28	35.4	44	53.7
≥10 years	22	47.8	51	64.6	38	46.4
Reporting daily use of HPD at baseline						
Yes	21	47.7	46	60.5	56	71.8
No	23	52.3	30	39.5	22	28.2
Reporting daily use of HPD at follow-up						
Yes	22	47.8	47	59.5	55	67.1
No	24	52.2	32	40.5	27	32.9
Age in 2009 (years), mean (SD)	46	50.9 (8.2)	79	48.6 (8.7)	82	46.0 (8.4)

*Defined as an average binaural hearing threshold > 20 dB in the noise sensitive frequencies (3, 4 and 6 kHz).

Table 3: Age and sex adjusted odds ratios (OR) of hearing handicap in the critically noise sensitive frequencies* according to year of first noise exposure among the baseline and follow-up populations

Year of first noise exposure > 80 dB	Subjects	Cases	OR	95% CI
Baseline population				
1990–1999	265	70	Reference	
1980–1989	148	32	1.02	0.59; 1.77
<1980	126	79	1.90	1.11; 3.22
Continuous pr. year	539	181	1.02	1.00; 1.04
Follow-up population				
2000–2010	97	30	Reference	
1990–1999	147	69	1.04	0.55; 1.95
1980–1989	105	62	1.30	0.66; 2.57
<1980	75	61	1.48	0.58; 3.77
Continuous pr. year	424	222	1.00	0.98; 1.04

*Defined as an average binaural hearing threshold > 20 dB in the noise sensitive frequencies (3, 4 and 6 kHz)

loss on the association between cumulative noise exposure and hearing threshold shift in the follow-up period. A Wald test was performed to test the hypothesis of no effect modification.

HPD use at baseline and follow-up was cross-tabulated with age and gender to identify possible changes in use over the follow-up period [Table 5]. To look for changes in noise emission from the industries included in this study, we calculated mean industry noise levels based on all individual blue-collar noise recordings at baseline and follow-up [Table 6].

In a sub-analysis, we subtracted 10 dB(A) from company noise levels if workers reported to use HPD, and we repeated the analyses between the cumulative noise exposure variable

and hearing threshold shift in the follow-up period as described above.

The STATA statistical package (version 13, StataCorp, College Station, TX, USA) was used for all analyses.

RESULTS

As shown in Table 1, the women-to-man ratio was lower with earlier first noise exposure in baseline and follow-up populations. In addition, mean age was higher with earlier first noise exposure in both the populations.

Among the 207 workers participating in both surveys, we observed a tendency towards a higher prevalence of males among the workers exposed to higher cumulative noise levels and more frequent use of HPD, but no

Table 4: Crude and adjusted associations between noise exposure variables and bilateral hearing threshold shift in the critically noise sensitive frequencies (3–6 kHz) among 207 workers followed from baseline to follow-up

	n	Crude	Adjusted ¹	Adjusted ²
		Δ3–6 kHz-HTL-BI	Δ3–6 kHz-HTL-BI	Δ3–6 kHz-HTL-BI
Cumulative occupational noise exposure, dB (A)-years				
Low (76.6–91.3)	46	Reference	Reference	Reference
Medium (91.4–94.8)	79	-1.14 (-3.79; 1.52)	-1.34 (-4.04; 1.35)	-1.44 (-4.15; 1.27)
High (94.9–107.0)	82	-0.88 (-3.51; 1.76)	-0.51 (-3.29; 2.20)	-0.70 (-4.15; 2.01)
Continuous		-0.13 (-0.39; 0.13)	-0.09 (-0.35; 0.17)	-0.10 (-0.36; 0.16)
Baseline occupational noise exposure (<i>L</i> _{Aeq})				
80–85 dB (A)	99	Reference	Reference	Reference
>85 dB (A)	106	1.08 (-0.92; 3.08)	0.77 (-1.20; 2.74)	0.56 (-1.41; 2.54)
Continuous (80.2–92.8)		0.01 (-0.32; 0.33)	0.00 (-0.32; 0.32)	-0.01 (-0.33; 0.31)
Years exposed >80 dB (A) from baseline to follow-up				
0–5	43	Reference	Reference	Reference
6–10	166	-0.42 (-2.76; 1.91)	-0.14 (-2.53; 2.26)	-0.24 (-2.64; 2.15)
Continuous (0–10)		-0.25 (-0.68; 0.17)	-0.06 (-0.50; 0.37)	-0.09 (-0.52; 0.34)
Years exposed >85 dB (A) from baseline to follow-up				
0–5	133	Reference	Reference	Reference
6–10	76	0.75 (-1.39; 2.89)	0.64 (-1.41; 2.68)	0.65 (-1.41; 2.70)
Continuous (0–10)		0.07 (-0.21; 0.35)	0.08 (-0.20; 0.36)	0.06 (-0.22; 0.34)

¹Adjusted for sex and age. ²Adjusted for sex, age, baseline hearing threshold and prior noise exposure >10 years

Table 5: HPD use at baseline and follow-up according to occupational noise level, sex and age group

	HPD use among baseline participants (n=539)								HPD use among follow-up participants (n=424)							
	<85 dB (A)				≥85 dB (A)				<85 dB (A)				≥85 dB (A)			
	Yes		No		Yes		No		Yes		No		Yes		No	
	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%
Sex, no (%)																
Female	22	37.3	37	62.7	12	44.4	15	55.6	15	20.0	60	80.0	9	56.3	7	43.8
Male	98	50.3	97	49.7	171	73.1	63	26.9	119	71.7	47	28.3	109	78.4	30	21.6
Age, no (%)																
<40	66	52.8	59	47.2	101	71.6	40	28.4	46	56.8	35	43.2	48	71.6	19	28.4
40–50	43	47.8	47	52.2	45	63.4	26	36.6	53	55.8	42	44.2	33	80.5	8	19.5
>50	11	28.2	28	71.8	37	75.5	12	24.5	35	53.9	30	46.2	37	78.7	10	21.3
All	120	47.2	134	52.8	183	70.1	78	29.9	134	55.6	107	44.4	118	76.1	37	23.9

Table 6: Mean noise levels per industry at baseline and follow-up, Aarhus, Denmark

Industry (NACE code)	No. of noise measurements	Mean noise level at baseline (<i>L</i> _{Aeq,work}), min, max (dB(A))	No. of noise measurements	Mean noise level at follow-up (<i>L</i> _{Aeq,work}), min, max (dB(A))	Difference (dB(A))
Manufacture of food (15)	79	84.7 (74.0–99.1)	58	84.5 (76.6–91.6)	-0.2
Manufacture of wood products (20)	72	85.3 (76.5–96.3)	40	84.9 (72.8–96.2)	-0.4
Publishing and printing (22)	87	81.9 (64.7–90.7)	53	81.7 (67.8–89.4)	-0.2
Manufacture of non-metallic prod. (26)	64	85.2 (74.8–97.2)	40	84.0 (75.4–106.0)	-1.2
Manufacture of basic metals (27)	44	85.6 (75.4–100.0)	24	83.0 (74.9–93.0)	-2.6
Manufacture of fabricated metals (28)	84	85.4 (73.7–97.4)	58	83.2 (71.7–94.9)	-2.2
Manufacture of machinery (29)	55	81.3 (73.3–90.7)	65	81.8 (67.5–91.3)	+0.5
Manufacture of motor vehicles (34)	65	83.8 (70.2–96.2)	44	82.6 (72.3–100.0)	-1.2
Manufacture of furniture (36)	18	81.0 (73.4–88.0)	7	80.6 (73.7–85.7)	-0.4
Construction (45)	27	84.6 (73.7–91.3)	22	80.1 (70.9–88.3)	-4.5
Day care (85)	32	82.2 (68.4–92.5)	56	81.9 (76.0–103.0)	-0.3
All noisy trades	627	83.9 (64.7–100.0)	467	82.8 (67.5–106.0)	-1.1

difference in the prevalence between baseline and follow-up [Table 2]. Conversely, the mean age seemed to be lower with the higher cumulative noise exposure [Table 2].

Table 3 shows adjusted odds ratios (ORs) of hearing loss in the critically noise-sensitive frequencies (as defined in section 'Audiometric measures') by year of first occupational noise exposure for the baseline and follow-up populations. For the baseline population, we observed no increased risk of hearing loss among those with first exposure after the 1980s compared to that of the reference group (adjusted OR: 1.02, 95% confidence interval (CI) 0.59; 1.77). For the baseline workers with the first exposure before the 1980s, we found a statistically significantly increased risk of hearing loss (adjusted OR: 1.90, 95% CI 1.11; 3.22) compared to that of the reference group. For each extra year since the first exposure, we found an OR of 1.02 for the hearing loss (95% CI 1.00; 1.04) among the baseline workers.

For the follow-up population, we also observed a tendency towards an increased risk of hearing loss with a longer time since the first exposure, but results were statistically insignificant. Thus, the adjusted OR for hearing loss for the group with the earliest exposure (before the 1980s) was 1.48 (95% CI 0.58; 3.77).

In the longitudinal analyses of the 207 workers, participating in both the surveys, we initially performed analyses on the association between the cumulative noise exposure and the hearing threshold shift in the follow-up period stratified by baseline hearing status and prior noise exposure, to account for a possible effect modification from these factors [Table 4]. Results showed only marginal differences between the strata, and Wald tests indicated no effect modification by these variables.

Therefore, we proceeded with the main longitudinal analyses without stratification for baseline hearing status and prior noise exposure. Adjusted results showed a weak, statistically insignificant, inverse association between higher cumulative noise exposure and the hearing threshold shift during the 10-year period. Thus, an average hearing threshold shift in the period was -0.09 dB for each extra noise-year (95% CI -0.35 ; 0.17) (adjusted for age and sex). A vague inverse association was also found between higher number of years exposed >80 dB (-0.06 dB threshold shift per extra year exposed >80 dB(A) (95% CI -0.57 ; 0.29) (adjusted for age and sex), but this association turned weakly positive when analysing number of years exposed >85 instead (0.08 dB threshold shift per extra year exposed >85 dB(A)) (adjusted for age and sex). No association was found between occupational noise level measured at baseline and hearing threshold shifts.

Accounting for the use of HPD by adjusting analyses for HPD use or subtracting 10 dB(A) from company noise levels for the sub-group reporting daily use of HPD did not noticeably change the association between the cumulative occupational noise and hearing threshold shift in the follow-up period

(association when adjusting for HPD: -0.11 dB per noise-year (95% CI -0.38 ; 0.16), and association when subtracting 10 dB if HPD was used: -0.09 (95% CI -0.26 ; 0.10)).

According to Table 5, 70% of the baseline population exposed to noise levels >85 dB(A) used HPD, raising to 76% among the follow-up population. Around 75% of men and 50% of women used HPD when exposed >85 dB(A) at both surveys. No distinctive differences in HPD use between the age groups were observed at either the baseline or follow-up populations.

Table 6 shows a general decline in noise levels from baseline to follow-up across the noisy industries included in this study. Only 'manufacture of machinery' showed an increasing noise level from 81.3 dB(A) at baseline to 81.8 dB(A) at follow-up. The most prominent fall in noise level over the follow-up period was seen in 'construction' (-4.5 dB(A)). Average decline for all the included industries from baseline to follow-up was 1.1 dB(A).

DISCUSSION

Main results from this study indicate that worker's cumulative occupational noise exposure during the follow-up period from 2000 to 2010 was not associated with statistically significant changes in hearing in the critically noise-sensitive frequencies. By categorising the baseline and the follow-up workers by their year of first noise exposure >80 dB(A), we found the highest risk of hearing loss among workers with first exposure before the 1980s in the baseline as well as the follow-up populations.

The prevalence of HPD use among workers exposed to average occupational noise levels >85 dB(A) increased from 70.1% in 2001–2003 to 76.1% in 2009–2010, whereas mean noise levels in the included industries decreased with 1.1 dB(A).

An average decline in noise level of 1.1 dB(A) over 10 years may appear small, but remembering that 1 dB represents a power ratio of approximately 1.26 (the decibel is a logarithmic unit), the effect on hearing preservation may be significant. In addition, some of the largest declines in mean noise levels are found among the industries with the highest baseline levels, meaning that no mean industry levels exceeded 85 dB(A) in 2009–2010. However, mean company noise levels used to classify worker's noise exposure still exceed 85 dB(A) for a substantial part of workers, and in this case, around three-quarters of workers reported to use HPD. Accordingly, the finding of no association between recent occupational noise levels and hearing threshold shift among our participants was not unexpected.

In a longitudinal cohort study from 2006,^[13] an inverse association between 10-year binaural hearing loss rates in the noise-sensitive frequencies (3, 4 and 6 kHz) and higher occupational noise exposure was found among 6217 noise-

exposed employees. The authors found no indication of a healthy worker bias in their analyses and, therefore, speculated if the result could be related to differential use of HPD as they found the majority of large threshold shifts among workers exposed to average noise levels <85 dB, where HPDs may not be used as consistently. Unfortunately, data on HPD use were not available in that study. We asked workers whether they used HPD in their current job and found that among workers exposed to average noise levels <85 dB(A), the use of HPD was in fact substantially lower than that at higher levels [Table 5]. Misclassification of actual noise at the ear from differential use of HPD could, therefore, also have introduced a similar bias in our study explaining the null findings.

Another 10-year longitudinal study recently conducted on construction workers in the USA^[14] demonstrated that noise levels in this particular industry still constitute a risk for hearing loss in the noise-sensitive frequencies (3, 4 and 6 kHz), even though the average estimated noise exposure $L(EQ)$ for the workers was only 2 dB(A) above 85 dB(A). The study population included only newly hired construction apprentices (mean age 27.6 years) assumed to have a limited prior noise exposure and good hearing at inception. Interestingly, they found a poor compliance of HPD use among the workers. Thus, only 50% of the construction workers reported to use HPD, and when observed, the fraction of exposure time, in which HPDs were used, was only 17–24%.^[15] Including newly hired apprentices is an advantage to the study, because an effect modification otherwise may occur from prior noise exposure and poor baseline hearing.^[16] We also included workers with prior noise exposure and workers from a broader age spectrum (mean age at baseline: 39.9 years) and, therefore, also performed stratified analyses.

A review from 2015 on occupational noise exposure and hearing concluded that the industrial noise levels in general had been reduced over the last few decades, and that this led to an improved hearing in noise-exposed groups in recent years.^[6] Only among construction workers, results showed that noise was still a substantial problem with regard to hearing. Our population was too small to allow for trade-specific sub-analyses, but in general, the conclusions of the review were in line with our findings and, interestingly, we observed the largest fall in noise exposure level from baseline to follow-up among construction workers (4.4 dB(A)).

Among the strengths of our study is the longitudinal design. Much of prior literature in this field is derived from cross-sectional studies lacking temporal specificity.^[17-19] Furthermore, our exposure quantification derived from individual dosimetries gives objective measures instead of subjective questionnaire information as often used to classify noise level. We did not have the capacity to measure bone conduction thresholds, which would have been a better measure of sensorineural hearing threshold. Instead, we

excluded participants with possible conductive hearing loss and asymmetric hearing loss from analyses to avoid misclassification. As the white-collar workers were considered to differ considerably from the remaining population with respect to covariates (e.g. leisure time noise) that we were not able to adjust for, we decided to restrict the population to occupationally noise-exposed workers. Exposure contrast in this group was considered sufficient, with individual exposure levels ranging from 67.5 dB(A) to 106.0 dB(A).

A lower loss to follow-up than 51% in our study would have been desirable, but in our selected industries with expected low job tenancy, we find a follow-up of 49% reasonable.

Among the workers participating in both the surveys, we identified 12 workers (4.4%), who moved from high to low exposure jobs. If this shift was made because of a higher susceptibility to noise exposure among the 12 workers, it could potentially introduce a 'healthy worker bias' by attenuating the exposure response relationship. By regression analysis, we, therefore, analysed if there was an association between a change from high-to-low exposure job during the 10-year period and baseline hearing levels. We found no significant association, indicating that this was not an issue of concern.

Another possibility of bias in our study is the misclassification of noise exposure due to HPD use. Information on HPD use was retrieved from the questionnaire and was not controlled by observation of actual behaviour. As mentioned above, prior studies have revealed a large discrepancy between self-reported use and actual behaviour^[15] which could also be the case in our study. To analyse whether (self-reported) HPD use had any impact on our results, we performed the sub-analyses subtracting 10 dB from the company noise exposure levels for workers reporting the HPD use and also tried to adjust the regression analyses for the use of HPD. Both sub-analyses revealed only slight changes of the main results. However, as mentioned above, a differential misclassification of actual 'noise at the ear' by a more consistent use of HPD at noise levels above 85 dB(A) is still a possibility and could have biased our results by attenuating the exposure response relationship.

To avoid TTS, we instructed participants to wear HPD from the beginning of the working day until an audiometry was performed. Participants' hearing could, however, still be affected by, for example, prior traffic or leisure time noise exposure. As most participants (around 90% in both surveys) worked only daytime (approximately 7 A.M. to 4 P.M.), we expected their prior noise exposure (mostly night time noise at home) to be low and should, therefore, not cause significant TTS. Using average company noise levels to classify worker's exposure could furthermore add to noise misclassification. We expected the sound levels to vary more from one day to another day for the individual workers than that between the different workers and

chose it over industry means, because analyses of variance showed most exposure contrast using company levels. Misclassification is, however, still a possibility but should be non-differential across noise exposure levels and would, therefore, bias results towards the null.

CONCLUSION

This study demonstrates a fall in recent industrial noise levels, increasing use of HPD and no association between the current occupational noise levels and hearing threshold shift.

We interpret these findings as an indication of a successful implementation of preventive measures enforced in Denmark during the last few decades to prevent noise-induced hearing loss.

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Conflicts of interest

There are no conflicts of interest.

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