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International Journal of Audiology

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/iija20

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To cite this article: Ina Molaug, Lisa Aarhus, Ingrid Sivesind Mehlum, Zara Ann Stokholm, Henrik A. Kolstad & Bo Engdahl (21 May 2023): Occupational noise exposure and tinnitus: the HUNT Study, International Journal of Audiology, DOI: 10.1080/14992027.2023.2211735

To link to this article: https://doi.org/10.1080/14992027.2023.2211735

Published online: 21 May 2023.

INTERNATIONAL JOURNAL OF AUDIOLOGY
https://doi.org/10.1080/14992027.2023.2211735

ORIGINAL ARTICLE

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Occupational noise exposure and tinnitus: the HUNT Study

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ABSTRACT

Objective: We aimed to assess the association between occupational noise exposure and tinnitus. Further, to assess whether the association depends on hearing status.

Design: In this cross-sectional study, tinnitus (>1 h daily) was regressed on job exposure matrix (JEM)-based or self-reported occupational noise exposure, adjusted for confounders.

Study sample: The 14,945 participants (42% men, 20–59 years) attended a population-based study in Norway (HUNT4, 2017-2019).

Results: JEM-based noise exposure, assessed as equivalent continuous sound level normalised to 8-h working days (LEX 8 h), over the working career or as minimum 5 years ≥85 dB) was not associated with tinnitus. Years of exposure ≥80 dB (minimum one) was not associated with tinnitus. Self-reported high noise exposure (>15 h weekly ≥5 years) was associated with tinnitus overall and among persons with elevated hearing thresholds (prevalence ratio (PR) 1.3, 1.0–1.7), however not statistically significantly among persons with normal thresholds (PR 1.1, 0.8–1.5).

Conclusions: Our large study showed no association between JEM-based noise exposure and tinnitus. This may to some extent reflect successful use of hearing protection. High self-reported noise exposure was associated with tinnitus, but not among normal hearing persons. This supports that noise-induced tinnitus to a large extent depends on audiometric hearing loss.

ARTICLE HISTORY
Received 15 December 2022
Revised 2 May 2023
Accepted 3 May 2023

KEYWORDS
JEM; work-related noise; occupational noise; Noise; Tinnitus

Introduction

Tinnitus can be described as "a ringing, buzzing or hissing sound in the ears or head" (Trevis, McLachlan, and Wilson 2018). The prevalence depends on the definitions used but is often reported in the range of 10–15% (Baguley, McFerran, and Hall 2013). Risk factors include age, hearing loss, noise exposure, previous head injury, ear infections, specific medications, socioeconomic status, smoking, health status and several somatic and mental conditions (Hoffman and Reed 2004; Nondahl et al. 2011; Hasson et al. 2011; Biswas et al. 2021).

Noise exposure is an important potentially modifiable risk factor for tinnitus. The association between occupational noise exposure and tinnitus is typically based on self-reported exposure data (Nondahl et al. 2011; Shargorodsky, Curhan, and Farwell 2010; Kim et al. 2015). However, self-reported data are vulnerable to recall-bias. A job exposure matrix (JEM) can provide a link between job codes and specific exposures in a more systematic way (Peters 2020). To the best of our knowledge, there are no previous studies that investigate the association between JEM-based noise and tinnitus.

Hearing loss is the main risk factor of tinnitus (Nondahl et al. 2011). The Central Gain Model suggests that following the reduced neural activity from the cochlea to the central auditory system after a hearing loss, the central auditory system increases neural activity in response (Auerbach, Rodrigues, and Salvi 2014). This attempt to maintain neural homeostasis, could ultimately lead to tinnitus (Noreña 2011).

It is a common theory that noise exposure leads to hair cell damage and secondly to tinnitus. (Rauschecker, Leaver, and Mühlau 2010). Following this mechanism, we would expect noise-induced tinnitus to be accompanied by hearing loss. Another suggested mechanism for noise-induced tinnitus, which can explain tinnitus among persons with normal audiometry, is cochlear synaptopathy, which involves loss of nerve terminals and degeneration of the cochlear nerve (Kujawa and Liberman 2009). However, this theory is only shown in animal studies. A few studies have evaluated whether the association between noise exposure and tinnitus is dependent on hearing loss (Park and Moon 2014; Rubak et al. 2008), showing various results.

In order to contribute to increased knowledge about the association between occupational noise exposure and tinnitus, we aim to assess the association in a large population-based study using both JEM-based and self-reported noise measurements. A second aim of our study was to assess whether the association depends on hearing status.

Materials and methods

Participants

The Trøndelag Health Study (HUNT) is one of the world's largest population-based health studies. This Norwegian study

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started in 1984 and has been conducted in four cycles (HUNT1-4) (Åsvold et al. 2022). All residents in the Nord-Trøndelag region of age 20 years or older have been invited to attend the HUNT studies (Åsvold et al. 2022). HUNT4 Hearing (2017–2019) is a part of HUNT4 restricted to the six larger municipalities (Levanger, Stjørdal, Steinkjer, Verdal, Nærøy, Namsos), representing about two thirds of the county with a target population of 74,650 invited subjects (Engdahl, Strand, and Aarhus 2020). HUNT4 Hearing included 28,388 participants, which represented a participation rate of 43%.

In the present study, participants from HUNT4 Hearing were excluded if they were 60 years or older, 19 years or younger, if they had an incomplete audiometry (at frequencies 3–6 kHz), missing questionnaires, no registered occupational codes or missing information about tinnitus. The upper age restriction was set to limit the likelihood of participants having retired from work. The participants gave a written consent. The Regional Committee for Medical Research Ethics approved the study (23178 HUNT hørsel).

Measurements

JEM-based noise exposure. We used a quantitative JEM to assign full-shift occupational noise exposure levels for each year in the participants' careers (1977–2017), according to sex, age, collar (white- or blue-collar worker), calendar year and specific assessments linked to occupational codes provided by Statistics Norway (Stokholm et al. 2020). This noise-JEM is based on 1,343 personal occupational noise dosimeter measurements for 1140 workers in over 100 different jobs, who were recruited in the time periods 2001–2003 and 2009–2010. Additionally, 35 of these jobs were a priori randomly selected to serve as benchmarks, as experts rated noise levels for the other jobs included in DISCO-88 (Stokholm et al. 2020). DISCO-88 is the Danish version of the International Standard Classification of Occupations (ISCO-88) (Danmarks Statistik 1996). Jobs with expected high noise exposure were prioritised for exposure measurements (Stokholm et al. 2020).

The occupational codes that were linked to the JEM were available as annual registrations of STYRK-98 codes (the Norwegian version of ISCO-88 (Statistics Norway 1998)) from 2003 to 2017. As the JEM was based on DISCO-88, the STYRK-98 codes were recoded to DISCO-88 codes by using a Nordic Crosswalk (Solovieva et al. 2022). Because these coding systems are fairly similar, with several identical codes, this process can be described as an adaptation rather than a complete recoding. Missing occupational codes were based on imputation of the existing occupational codes. For the years 2000–2017, missing codes for each year were imputed if annual employment status showed that the participant was working. Single imputation was utilised, for which the strategy was last observation carried forward. If there were no previous occupational codes, we used the next observation carried backward. Codes for the years 1993–1999 were imputed if income was above 3.5 G (the Norwegian Government decides G units on an annual basis), in order to cover the core workforce (Widding Havnerås 2016). People with lower incomes were considered unemployed, as income also covers for instance unemployment benefits. Codes for the years 1977–1992 were imputed based on employment status (working/not working) from censuses for each decade (1970, 1980 and 1990).

We defined two JEM-based variables: A continuously estimated and a categorical variable. For the continuously scored variable, we used the annually assigned noise levels for each participant to calculate a logarithmic average of lifetime occupational noise exposure. A-weighted noise exposure level was normalised to an 8-h working day for each year in this period (LEX 8h). The calculation of a logarithmic average (instead of an arithmetic average) was necessary as the noise levels (in decibels) are on a logarithmic scale.

The categorical JEM-based variable was defined as follows: High exposure: at least five annual assigned average noise levels (LEX 8h) of 85 decibel (dB) or higher (not necessarily consecutive years); low exposure (reference group): no annual average noise levels of 80 dB or higher; moderate exposure: remaining participants (do not fulfil criteria for high or low exposure). The exact noise levels and durations which lead to tinnitus is not well cleared out, however it is well known that hearing loss is an important risk factor. As such, we chose 85+ dB as the cut off for high exposure, as continuous noise exposure below this level is associated with a low risk of hearing loss (Lie et al. 2016). The limit of 85 dB is also in line with Norwegian regulations on daily allowed occupational noise exposure (LEX 8h). Considering that noise-induced hearing loss develops over years, 5 years of high-level noise exposure was chosen as a minimal duration for the high exposure group. Exposure to noise below 80 dB was chosen as the low exposed category, as hearing loss due to occupational noise is not expected at these noise levels.

Self-reported noise exposure

We used questionnaire data from HUNT4. "Have you in your recent or previous job been regularly exposed to loud noise" (yes/no). Loud noise exposure was defined as noise which made it difficult to have a conversation. Participants who replied "no" were categorised as the reference group. Two more questions were used to categorise the exposed groups: "How long have you been exposed to loud noise at your work?" (below 5 years/5–10 years/10–20 years/above 20 years.) "Approximately how many hours during a working week have you been exposed to loud noise?" (less than 5 h a week/5–15 h a week/more than 15 h a week.) High exposure was defined as >15 h weekly exposure and ≥5 years. The remaining exposed participants were classified as having "moderate" exposure.

Tinnitus

The outcome of the study was daily tinnitus, which usually lasted over 1 h (yes or no). This was measured at one single time point (2017–2019) after the registered noise exposure, and we used the three following questions from the HUNT4 questionnaire to assess whether the participants had such tinnitus: (1) "Have you during the last 12 months experienced ringing in your ears?" (no/yes/do not know) (2) "How often do you have ringing in your ears?" (always/daily/weekly/monthly or more seldom) (3) "How long do the periods with ringing usually last?" (<5 min/5 min to 1 h/> 1 h). Participants with missing information on question 1 were excluded from the study. Participants with the combination "yes" on question 1, "always" or "daily" on question 2 and ">1 hour" on question 3 were categorised as having tinnitus (over 1 h daily). The remaining participants were defined as not having the outcome.

Hearing threshold

The pure-tone audiometry was conducted in line with ISO 8253-1 (International Organization for Standardization 2010), with fixed test frequencies at 0.25, 0.5, 1, 2, 3, 4, 6 and 8 kHz (utilizing an automatic procedure) and has been described previously (Engdahl, Strand, and Aarhus 2020; Engdahl et al. 2005). Audiometers were calibrated according to ISO 389-1 and checked daily by operators prior to audiometry. We used our own reference population for assessing audiometric zero, which consisted of otologically normal subjects aged 19–23 years (Engdahl, Strand, and Aarhus 2020). This to compensate for known calibration error at 6 kHz in ISO389 for the TDH-39P earphones used (Engdahl et al. 2005). Without this correction the prevalence of hearing losses at 3–6 kHz would have been slightly overestimated (Engdahl, Strand, and Aarhus 2020). In the present study, we defined elevated hearing thresholds as the pure tone average at 3–6 kHz >25 decibel hearing level (dB HL), mean of both ears. The remaining participants were categorised as having normal hearing.

Covariates

We used a Directed Acyclic Graph (DAG), together with a priori knowledge and "clinical" judgements, to map the causal associations between the variables. In addition to adjustment for age (continuous) and sex, we used HUNT4 questionnaire data to adjust for education (college or university/less education), leisure noise exposure to loud music (use of earphones >6 h a week, most often at high volume), leisure impulse noise exposure (yes to at least one of the following; have tried hunting; have attended competitive or hobby shooting; have experienced transient hearing loss due to fireworks, etc/no), ever hospitalised due to head injury (yes/no), smoking (currently or previously smoked/never smoked) and feeling nervous/uneasy the last two weeks (yes; from a little to a lot/no). The mentioned factors are suspected or confirmed associated with tinnitus (Baguley, McFerran, and Hall 2013; Hoffman and Reed 2004; Nondahl et al. 2011; Biswas et al. 2021; McCormack et al. 2014) and occupation/occupational noise (Stokholm et al. 2020; Flamme et al. 2012; Dzhambov and Dimitrova 2017; Ham, Junankar, and Wells 2009; Fujishiro et al. 2012). Feeling nervous/uneasy was used as a proxy for neuroticism. We also adjusted for years of unemployment (continuous) during 2000–2017 (based on employment status provided by Statistics Norway), as unemployment is associated with tinnitus (Kim et al. 2015) and results in less years with occupational noise exposure. In addition, there could be a healthy worker effect among participants with little or no unemployment. Missing values were imputed to less education, no or non-exposed. In the total sample, each of the covariates had <5% missing.

Descriptive information

Number of participants who reported use of hearing protection "always" was included descriptively (other options included "often," "seldom/never" and "not applicable.").

Statistical analyses

Data were analysed in stata version 17.0

We used Chi-square tests to assess crude differences in the proportion of tinnitus as a function of hearing status (normal hearing and elevated hearing thresholds) and noise exposure (low, moderate and high) separately. The difference in mean age between tinnitus cases and non-cases was tested using t-test.

We used Poisson regression with robust variances to assess the adjusted association between noise exposure and tinnitus expressed as prevalence ratios (PR) with 95% confidence intervals (CI). Noise exposure was analysed as JEM-based (categorical), JEM-based (continuous) and self-reported data. In Model A we adjusted for age and sex. In Model B we adjusted for age, sex, education, head injury, leisure noise exposure (earphones), leisure impulse noise exposure, smoking, feeling nervous/uneasy and years of unemployment. The association was assessed in the total sample and in strata of hearing status.

Among persons with at least 1 year of assigned noise level (LEX 8h) ≥80 dB ($N = 6033$), we analysed the association between number of years with exposure (LEX 8h) ≥80 dB and tinnitus. We used a Poisson regression analysis, and calculated estimates for Model A and Model B as described above.

Results

Participants

Among the 28,388 individuals that participated in the hearing study, we excluded the following participants: Age 60 years or older ($N = 11,577$), age 19 years or younger ($N = 48$), questionnaires missing ($N = 1036$), incomplete audiometry ($N = 31$), missing information about tinnitus ($N = 160$) or no registered occupational codes ($N = 591$). The age restrictions were set to include the working population. The final sample included 14,945 participants.

Descriptive results

Table 1 displays the characteristics of the 14,945 participants in different exposure groups. There were higher proportions of men and older participants in the highly exposed (JEM-based) group, compared to the two lower exposed (JEM-based) categories. Among the JEM-based highly exposed participants, 25% reported always using hearing protection. In the self-reported highly exposed group, 36% reported always using hearing protection.

Table 2 presents the crude prevalence of tinnitus (over 1 h daily) among the participants, stratified by noise exposure and hearing status. The prevalence of tinnitus was higher among participants with elevated hearing thresholds (Chi2, $p < 0.001$). A higher prevalence of tinnitus was found among highly exposed participants (Chi2, $p < 0.001$) compared to low and moderately exposed participants, regardless of whether noise exposure was assessed by JEM or self-report. The Chi-square tests are not shown in the tables. In addition, tinnitus cases were on average 6.8 years older than non-cases (t-test, $p < 0.001$).

Associations between noise exposure and tinnitus

JEM-based noise exposure (continuous LEX 8h or categorically scored) was not associated with the prevalence of tinnitus, neither in the total material, nor stratified by hearing status in the fully adjusted model (Table 3, Model B). Further, number of years with exposure ≥80 dB (on average 12.0 ± 9.9 years) was not associated with tinnitus (Model A estimates: PR 1.0, 1.0–1.0, Model B estimates: PR 1.0, 1.0–1.0).

Self-reported high noise exposure (>15 h weekly ≥5 years) was associated with an increased prevalence of tinnitus overall (PR 1.4, 95% CI 1.2–1.7) (Table 4, Model B) and among persons

Table 1. Characteristics of 14,945 participants in different exposure groups in HUNT4 Hearing (2017–2019), Norway.

	JEM-based noise exposure			
	Low exposed *N* (%)	Moderately exposed *N* (%)	Highly exposed *N* (%)	Total, *N* (%)
Total	8912 (100)	5081 (100)	952 (100)	14,945 (100)
Age, mean ± *SD*	42.6 ± 11.4	40.9 ± 11.1	50.0 ± 7.9	42.5 ± 11.3
Men	2620 (29.4)	2736 (53.9)	889 (93.4)	6245 (41.8)
Normal hearing[a]	8037 (90.2)	4450 (87.6)	656 (68.9)	13,143 (87.9)
Elevated hearing thresholds[a]	875 (9.8)	631 (12.4)	296 (31.1)	1802 (12.1)
Feeling nervous/uneasy last 2 weeks	3822 (42.9)	2165 (42.6)	312 (32.8)	6299 (42.2)
Lower education	3286 (36.9)	3273 (64.4)	781 (82.0)	7340 (49.1)
Head injury	539 (6.1)	379 (7.5)	74 (7.8)	992 (6.6)
Leisure noise, earphones at loud volume >6 h/week	205 (2.3)	168 (3.3)	10 (1.1)	383 (2.6)
Leisure impulse noise (shooting, fireworks, etc)	3298 (37.0)	2437 (48.0)	625 (65.7)	6360 (42.6)
Years of unemployment (2000–2017), mean ± *SD*	2.3 ± 2.9	2.3 ± 2.7	1.1 ± 2.0[b]	2.2 ± 2.8
Smoking history	4176 (46.9)	2761 (54.3)	548 (57.6)	7485 (50.1)
Reports always using hearing protection[c]	229 (2.6)	655 (12.9)	239 (25.1)	1123 (7.5)
	Self-reported noise exposure[d]			
	Low exposed *N* (%)	Moderately exposed *N* (%)	Highly exposed *N* (%)	**Total**[d], *N* (%)
Total	10,802 (100)	3074 (100)	902 (100)	14,778 (100)
Age, mean ± *SD*	42.5 ± 11.2	41.3 ± 11.6	46.5 ± 9.5	42.5 ± 11.3
Men	3475 (32.2)	2057 (66.9)	638 (70.7)	6170 (41.8)
Normal hearing[a]	9721 (90.0)	2608 (84.8)	664 (73.6)	12,993 (87.9)
Elevated hearing thresholds[a]	1081 (10.0)	466 (15.2)	238 (26.4)	1785 (12.1)
Feeling nervous/uneasy last 2 weeks	4491 (41.6)	1349 (43.9)	392 (43.5)	6232 (42.2)
Lower education	4593 (42.5)	1971 (64.1)	667 (74.0)	7231 (48.9)
Head injury	631 (5.8)	265 (8.6)	87 (9.7)	983 (6.7)
Leisure noise, earphones at loud volume >6 h/week	236 (2.2)	112 (3.6)	32 (3.6)	380 (2.6)
Leisure impulse noise (shooting, fireworks, etc)	3958 (36.6)	1791 (58.3)	546 (60.5)	6295 (42.6)
Years of unemployment (2000–2017), mean ± *SD*	2.2 ± 2.8	2.2 ± 2.7	1.9 ± 2.7 [b]	2.2 ± 2.8
Smoking history	5126 (47.5)	1703 (55.4)	562 (62.3)	7391 (50.0)
Reports always using hearing protection[c]	74 (0.7)	711 (23.1)	320 (35.5)	1105 (7.5)

Information is based on HUNT4 (questionnaires or examination) and a JEM (job exposure matrix). Exposure categories, JEM: low = no exposure ≥80 dB; high = minimum 5 years ≥85 dB; moderate = not fulfilling criteria for low or highly exposed. Exposure categories, self-report: low = no prior exposure; high = >15 h/week ≥5 years; moderate = not fulfilling criteria for low or highly exposed.
[a]Elevated hearing thresholds = thresholds at 3–6 kHz (mean of both ears) > 25 dB. Normal hearing = remaining participants.
[b]The highly exposed categories (JEM and self-report) include time criteria (at least 5 years of exposure), which should be kept in mind when comparing different exposure categories.
[c]Answered "always" to the question: "Did you use hearing protection." (Instead of "often," "seldom/never" or "not applicable.")
[d]Participants with missing information about self-reported noise exposure (*N* = 167) were excluded.

Table 2. Crude prevalence of tinnitus among 14,945 participants, stratified by noise exposure and hearing status, in HUNT4 Hearing (2017–2019), Norway.

	JEM-based noise exposure			
	Low exposed, *N* (%)	Moderately exposed, *N* (%)	Highly exposed, *N* (%)	Total, *N* (%)
Normal hearing[a]	360 (4.5)	182 (4.1)	40 (6.1)	582 (4.4)
Elevated hearing thresholds[a]	203 (23.2)	126 (20.0)	62 (21.0)	391 (21.7)
Total	563 (6.3)	308 (6.1)	102 (10.7)	973 (6.5)
	Self-reported noise exposure[b]			
	Low exposed, *N* (%)	Moderately exposed, *N* (%)	Highly exposed, *N* (%)	Total[b], *N* (%)
Normal hearing[a]	394 (4.1)	148 (5.7)	36 (5.4)	578 (4.5)
Elevated hearing thresholds[a]	211 (19.5)	111 (23.8)	67 (28.2)	389 (21.8)
Total	605 (5.6)	259 (8.4)	103 (11.4)	967 (6.5)

Information is based on HUNT4 (questionnaires or examination) and a JEM (job exposure matrix). Exposure categories, JEM: low = no exposure ≥80 dB; high = minimum 5 years ≥ 85 dB; moderate = not fulfilling criteria for low or highly exposed. Exposure categories, self-report: low = no prior exposure; high = >15 h/week ≥5 years; moderate = not fulfilling criteria for low or highly exposed.
[a]Elevated hearing thresholds = thresholds at 3–6 kHz (mean of both ears) > 25 dB. Normal hearing = remaining participants.
[b]Participants with missing information about self-reported noise exposure (*N* = 167) were excluded.

with elevated hearing thresholds (PR 1.3, 1.0–1.7). Moderate self-reported noise exposure was associated with an increased prevalence of tinnitus in persons with normal hearing (PR 1.3, 1.1–1.6). The association between self-reported high noise exposure and tinnitus prevalence was not statistically significant in persons with normal hearing (PR 1.1, 0.8–1.5).

Discussion

Main findings

Among the 14,945 participants in this study, 6.5% reported tinnitus (more than 1 h daily). There was no association between JEM-based noise exposure (continuously scored as LEX 8h,

Table 3. Prevalence ratios of tinnitus[a] in relation to JEM-based occupational noise exposure among 14,945 participants in HUNT4 Hearing (2017–2019), Norway.

	Prevalence ratios of tinnitus[a], PR (95 % CI)					
	Categorical JEM-based noise[b]					
	Moderately exposed		Highly exposed		Continuous JEM-based noise	
	Model A[c]	Model B[d]	Model A[c]	Model B[d]	Model A[c]	Model B[d]
Total sample	0.95 (0.83–1.09)	0.96 (0.84–1.11)	0.88 (0.72–1.09)	0.91 (0.73–1.14)	**0.98 (0.97–1.00)**	0.99 (0.97, 1.01)
Stratified analyses[e]						
Normal hearing	0.92 (0.77–1.10)	0.96 (0.80–1.16)	0.86 (0.61–1.20)	0.93 (0.65–1.31)	**0.97 (0.95–0.99)**	0.98 (0.96, 1.01)
Elevated hearing thresholds	0.87 (0.72–1.06)	0.88 (0.71–1.08)	**0.76 (0.58–0.98)**	0.77 (0.59–1.02)	**0.97 (0.95–1.00)**	0.98 (0.96, 1.01)

Significant values in bold ($p < 0.05$).
[a]Tinnitus > 1 h daily.
[b]Categorical JEM (job exposure matrix)-based exposure: low = no exposure ≥ 80 dB (reference group); high = minimum 5 years ≥ 85 dB; moderate = not fulfilling criteria for low or highly exposed.
[c]Prevalence ratio, Poisson regression analysis adjusted for age and sex. Total sample and stratified by hearing status.
[d]Prevalence ratio, Poisson regression analysis adjusted for age, sex, education, head injury, leisure noise, smoking, feeling nervous/uneasy and years of unemployment. Total sample and stratified by hearing status.
[e]Elevated hearing thresholds = thresholds at 3–6 kHz (mean of both ears) > 25 dB. Normal hearing = remaining participants.

Table 4. Prevalence ratios of tinnitus[a] in relation to self-reported occupational noise exposure among 14,778 participants in HUNT4 Hearing (2017–2019), Norway.

	Prevalence ratios of tinnitus[a], PR (95 % CI)			
	Moderately exposed		Highly exposed	
	Model A[b]	Model B[c]	Model A[b]	Model B[c]
Total sample	**1.38 (1.20–1.60)**	**1.34 (1.16–1.55)**	**1.47 (1.20–1.79)**	**1.41 (1.15–1.72)**
Stratified analyses[d]				
Normal hearing	**1.37 (1.13–1.66)**	**1.34 (1.10–1.62)**	1.11 (0.79–1.55)	1.09 (0.78–1.53)
Elevated hearing thresholds	1.22 (0.99–1.50)	1.22 (0.99–1.50)	**1.35 (1.06–1.71)**	**1.33 (1.04–1.70)**

Significant values in bold ($p < 0.05$). Exposure categories, self-report: low = no prior exposure (reference group); high = >15 h/week ≥5 years; moderate = not fulfilling criteria for low or highly exposed.
[a]Tinnitus > 1 h daily.
[b]Prevalence ratio, Poisson regression analysis adjusted for age and sex. Total sample and stratified by hearing status. Participants with missing on self-reported noise exposure ($N = 167$) were excluded from these analyses.
[c]Prevalence ratio, Poisson regression analysis adjusted for age, sex, education, head injury, leisure noise, smoking, feeling nervous/uneasy and years of unemployment. Total sample and stratified by hearing status. Participants with missing on self-reported noise exposure ($N = 167$) were excluded from these analyses.
[d]Elevated hearing thresholds = thresholds at 3–6 kHz (mean of both ears) >25 dB. Normal hearing = remaining participants.

categorically scored as minimum 5 years ≥85 dB) and tinnitus. Years of exposure ≥80 dB (minimum one) was not associated with tinnitus. Self-reported high noise exposure was associated with tinnitus among participants with elevated hearing thresholds (mean of thresholds at 3–6 kHz >25 dB), but not statistically significant among participants with normal hearing.

Tinnitus prevalence

In this study population, 6.5% reported tinnitus (over 1 h daily). Correspondingly, a study which included 14,178 participants from "the National Health and Nutrition Examination Survey" (NHANES), reported that 7.9% experienced frequent tinnitus (Shargorodsky, Curhan, and Farwell 2010). In a study based on the Beaver Dam Offspring Study (Nondahl et al. 2011), with participants aged 21–84 years and a stricter definition of tinnitus (buzzing/ringing/noise in ears in the last year, of minimum moderate severity or which caused trouble sleeping), tinnitus prevalence was 10.6%. Overall, both tinnitus definition and tinnitus prevalence vary somewhat in different studies.

JEM-based noise exposure and tinnitus

Our large study showed no association between lifetime JEM-based noise exposure and tinnitus. To the best of our knowledge, no prior studies have evaluated JEM-based noise exposure and tinnitus. We believe our finding suggests that Norwegian workers in high-noise exposure occupations do not have a higher risk of tinnitus compared with unexposed persons. This can to some extent be related to successful use of hearing protection, which was not accounted for in the JEM. Therefore, the assigned noise levels by the JEM could be somewhat higher than what participants actually experienced. Adjustment for (self-reported) use of hearing protective equipment is however challenging, as we would expect workers exposed to higher levels of noise to have a higher need for such equipment. A recent Norwegian study showed only a weak association between JEM-based occupational noise exposure and hearing loss among men (Molaug et al. 2022). As hearing loss is the most important risk factor for tinnitus, this complies with the present negative finding.

Self-reported noise exposure and tinnitus

Our study showed an association between self-reported noise exposure and tinnitus, in compliance with several studies (Nondahl et al. 2011; Park and Moon 2014; Palmer et al. 2002). Self-reported measurements are prone to recall-bias. A previous study has reported high agreement between researcher observations and construction workers' self-reported activities and use of tools (Neitzel et al. 1999). However, the agreement might be higher in this study with daily reporting of tasks and tools, compared to the present study. We believe the present finding of an association between self-reported high noise exposure and tinnitus among persons with elevated hearing thresholds, which was not statistically significant among normal hearing persons, is interesting and worth discussing.

It is a common theory that noise exposure leads to hair cell damage and secondly to tinnitus. In other words, that noise-related tinnitus to a large extent depends on initial audiometric hearing loss. However, noise-related tinnitus may also occur in situations without identifiable audiometric hearing loss, for example after noise-related temporary hearing loss (Kujawa and Liberman 2009) and cochlear synaptopathy, a "hidden hearing loss" which is not detectable on audiometry (Barbee et al. 2018).

The present finding of an association between high self-reported noise exposure and tinnitus only among participants with elevated hearing thresholds supports the theory that noise-induced tinnitus to a large extent depends on hair cell damage and audiometric hearing loss, at least among highly exposed individuals. As to comparable studies, two studies have evaluated the association between noise exposure and tinnitus in persons with and without audiometric hearing loss. Park & Moon (Park and Moon 2014) found associations between self-reported noise exposure and tinnitus, both among participants with and without hearing impairment (defined as pure tone average > 25 dB at 0.5, 1, 2 and 4 kHz in either ear). The latter is not in line with the results of the present study. Rubak et al. found a dose dependent association between noise exposure and tinnitus among participants with a hearing handicap, which was not found for participants with normal hearing (Rubak et al. 2008). Noise exposure was computed based on dosimeter recordings and self-reported noise in previous jobs, and both hearing loss and tinnitus definitions differed from the present study. Comparison to the present study is therefore somewhat challenged, although this result complies with the findings on high self-reported noise exposure and tinnitus in the present study.

High self-reported noise exposure in the present study was associated with tinnitus only among persons with elevated hearing thresholds. In contrast, our study also showed that moderate self-reported noise exposure was associated with tinnitus among participants with normal hearing. We can only speculate about the explanations. We would have expected increasing prevalence with increasing noise exposure if a causal association. But perhaps persons exposed to moderate noise levels have a working situation in which background noise is especially annoying, for example working in an office with the need to concentrate, which could increase a negative focus towards noise exposure and tinnitus.

Strengths and limitations

Strengths included the objective JEM-based noise exposure data that should not be affected by recall bias, standardised audiometric measurements, good confounder control and a large number of participants from a population-based health study, in which the population previously has been assessed to be representative for the entire country (Engdahl, Strand, and Aarhus 2020). Although occupational noise exposure was registered throughout several years prior to the outcome (which was measured at one point), we cannot eliminate that the onset of tinnitus could have occurred before the exposure. Further, we cannot eliminate that persons with tinnitus have changed to less noisy jobs or have left the workforce. Misclassification could have occurred if current tinnitus has improved after hearing rehabilitation or years of adjusting following previous noise exposure. An age limitation was set in this study to avoid including participants who were expected to have retired from work. The highly exposed participants were somewhat older and had a higher proportion of men, compared to the lower exposed groups. The low prevalence of highly exposed women is a common limitation in studies on occupational noise exposure. In an earlier wave of the HUNT Study, nonparticipants were found to have lower socioeconomic status and a higher prevalence of chronic diseases (Langhammer et al. 2012). If this also applies to our study, it could have led to a healthy volunteer effect, and possibly to conservative results. As HUNT4 Hearing is part of a larger health study, we do not suspect that motivation to participate was related to the present exposure or outcome.

The JEM is based on noise level measurements in the period 2001–2010 (Stokholm et al. 2020), and noise levels before or after this period are extrapolated, which could introduce bias. Missing occupational codes could have led to some information bias. The missing codes (including periods of unemployment) were replaced by the lowest noise values in the JEM (67.7 dB), as we are all exposed to some noise during a year, but these low values are not expected to contribute significantly to average noise levels. Further, the JEM is constructed based on Danish occupations, but we believe that the Norwegian and Danish working life and noise levels are fairly similar. We cannot eliminate that the negative association between JEM-based noise exposure and tinnitus is related to misclassification bias. A JEM assigns the same exposure to all participants with the same job title (Peters 2020) and is therefore vulnerable to non-differential misclassification. Our descriptive data showed that the proportion who reported always using hearing protection was higher among self-reported highly exposed participants (36%), compared to JEM-based highly exposed participants (25%). If this proportion reflects the noise levels (expected higher need of hearing protection among highly exposed workers), the grouping strategy to sort out highly exposed participants might have worked better for the self-reported variable compared to the JEM-based variable.

Another contributing factor to underestimation of the results could potentially be healthy worker effect, as being highly exposed included a time criteria (as opposed to the low and moderately exposed groups), and there might be a selection of participants who are less bothered by loud noise in the highly exposed group. We believe that both JEM-based and self-reported measurements each have their advantages and disadvantages, and that the true estimates might lie somewhere in between the results for the two different exposure measures. As such, we find that including both objective and subjective measurements is a strength to our study.

Conclusion

Our large population study showed no association between JEM-based noise exposure and tinnitus. Further, years of exposure $\geq$80 dB was not associated with tinnitus. This may to some extent reflect successful use of hearing protection, which the JEM does not account for. There were more men than women among the highly exposed participants. High self-reported noise exposure was associated with tinnitus overall and among hearing impaired participants, but not statistically significant among participants with normal hearing. We believe this finding supports the theory that noise-induced tinnitus to a large extent depends on audiometric hearing loss among highly exposed individuals. We cannot eliminate misclassification for our JEM-based measurements, nor recall bias for the self-reported data. Future studies should include individual noise level recordings that accounts for use of hearing protection devise to resolve this enigma.

Acknowledgements

The Trøndelag Health Study (The HUNT Study) is a collaboration between HUNT Research Centre, (Faculty of Medicine and Health Sciences, NTNU, Norwegian University of Science and Technology), Trøndelag County Council, Central Norway Regional Health Authority, and the Norwegian Institute of Public Health. We also thank the HUNT4 Hearing team for their diligence.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The datasets generated and/or analysed during this study are not publicly available due to Norwegian legal restrictions and the current ethical approval for the study.

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