ORIGINAL RESEARCH

# Association Between Long-Term Exposure to Wind Turbine Noise and the Risk of Stroke: Data From the Danish Nurse Cohort

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***Background*—**Epidemiological studies suggest that road traffic noise increases the risk of stroke. Similar effects may be expected from wind turbine noise (WTN) exposure, but epidemiological evidence is lacking. The present study investigated the association between long-term exposure to WTN and the risk for stroke.

***Methods and Results*—**First-ever stroke in 28 731 female nurses in the Danish Nurse Cohort was identified in the Danish National Patient register until the end of 2013. WTN, traffic noise, and air pollution exposures were estimated for all historic and present residential addresses between 1982 and 2013. Time-varying Cox proportional hazard regression was used to examine the associations between the 11-, 5-, and 1-year rolling means of WTN levels and stroke incidence. Of 23 912 nurses free of stroke at the cohort baseline, 1097 nurses developed stroke by the end of follow-up. At the cohort baseline, 10.3% of nurses were exposed to WTN (≥1 turbine within a 6000-meter radius of the residence) and 13.3% in 2013. Mean baseline residential noise levels among exposed nurses were 26.3 dB(A). No association between long-term WTN exposure and stroke incidence was found. The adjusted hazard ratios and 95% CIs for the 11-, 5-, and 1-year running mean residential WTN exposures preceding stroke diagnosis, comparing nurses with residential WTN levels above and below 20 dB(A) were 1.09 (0.90–1.31), 1.08 (0.89–1.31) and 1.08 (0.89–1.32), respectively.

***Conclusions*—**This comprehensive cohort study lends no support to an association between long-term WTN exposure and stroke risk. **(*J Am Heart Assoc*. 2019;8:e013157. DOI: 10.1161/JAHA.119.013157.)**

**Key Words:** Danish Nurse Cohort • environmental long-term wind turbine exposure • epidemiology • prospective cohort study • stroke

Stroke is a major cause of disability and death in adults, and it is estimated that 5.8 million people die from stroke globally every year.[1] Exposure to persistent environmental noise is thought to increase the risk of cardiovascular disease and several epidemiological studies have implicated traffic noise (road, rail, and air) as a risk factor for increased stroke incidence, particularly in the elderly.[2,3] The effects of wind turbine noise (WTN) on stroke may be similar, but this has only been investigated once.[4] Although the authors report a protective effect of WTN exposure in that study, they state that this should be interpreted with caution, as results were based on a small number of cases. WTN has consistently been associated with annoyance and reported to affect sleep in some studies.[5–7] Thus, WTN exposure is believed to act as a stressor with activation of the hypothalamus-pituitary-adrenal axis and stress response cascade,[8] and noise has been shown to induce systemic low-grade inflammation[9]; finally, the cortisol released in the stress reaction cascade may increase blood glycogen within atrial myocytes,[10,11] all of which are suggested risk factors for stroke.

There is presently a global focus on the development of renewable energy expansions and zero-carbon shares in energy systems, and wind energy is a suitable solution to achieve this.[12] Denmark is one of the world leaders in total wind capacity, and in 2016 wind power represented 37.6% of Denmark's total electricity consumption,[13] and it is estimated that around 800 000 Danish homes (≈12%) are located within a 6000-meter radius of a wind turbine (WT). The Danish government has set a goal to generate 50% of the country's electricity by wind

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Accompanying Data S1, Tables S1 through S3, and Figure S1 are available at https://www.ahajournals.org/doi/suppl/10.1161/JAHA.119.013157

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## Clinical Perspective

### What Is New?

- This large Danish study, including 24 000 Danish nurses followed for up to 20 years, is the first prospective cohort study examining the impact of long-term exposure to wind turbine noise and the risk of stroke.
- We found no evidence that long-term exposure to wind turbine noise increases the risk of stroke, in agreement with a single earlier study on the topic.

### What Are the Clinical Implications?

- While annoyance due to noise from wind turbines should be taken seriously, it is reassuring that this type of noise is unlikely to cause serious cerebrovascular disease such as stroke.

energy by 2021, implying a continued increase in the numbers and size of WTs, as well as in the proportion of the Danish population who live in close proximity to WTs.[13]

In 2016 the use of wind power avoided over 637 million tons of $CO_2$ emissions globally,[14] which has positive environmental and health implications. But despite this, WTs are also a source of environmental noise and the local-level potential risk to human health remains the subject of debate. Considering this debate and the continued increase in numbers of WTs, we aimed to elucidate the potential association between long-term exposure to WTN and risk of stroke, using a large, nationwide, prospective cohort of Danish nurses with long-term follow-up for stroke hospitalizations in high-quality and complete nationwide registries.

## Methods

### Study Population—The Danish Nurse Cohort

The study was based in the Danish Nurse Cohort, which was inspired by the American Nurses' Health Study to investigate the health effects of hormone replacement therapy (HRT) in a European population. The cohort has been described in detail previously,[15] and a detailed description is also provided in Data S1. In brief, the cohort was initiated in 1993 by sending a questionnaire to 23 170 nurses and reinvestigated in 1999. Information included socioeconomic and working conditions, parents' occupation, weight and height, lifestyle (diet, smoking, alcohol consumption, and leisure time physical activity), self-reported health, family history of cardiovascular disease, and use of oral contraceptives and HRT. In the present study, we used the earliest baseline information from 1993 (19 898 nurses) or 1999 (8833 nurses) for 28 731 nurses included in the cohort.

Since establishment of the Central Population Register in 1968,[16,17] all citizens of Denmark have been given a unique personal identification number, which allows accurate linkage between registers. The cohort members were linked to the Central Population Register[16,17] to obtain the nurses' vital status information at December 31, 2013 (active, date of death/emigration). Using the unique personal identification numbers of the cohort members, all residential histories were traced in the Central Population Register between 1982 and 2013. Each residential address contained a unique identification code composed of a municipality, road, and house number code. The dates the persons had moved to and from each address were noted. The addresses were then linked to a database of all official addresses and their geographic coordinates in Denmark.

### Identification of Outcome—National Patient Register

The end point was incidence of stroke (*International Classification of Disease, Tenth Revision* [*ICD-10*]: D161, D163, and *ICD, Eighth Revision* [*ICD-8*]: 431.0, 431.9, 432.0, 432.9, 433.09, 433.99, 434.09, 436.0, and 436.9), defined as first-ever hospital contact (emergency, in- or outpatient) for stroke, identified in the Danish National Patient Registry.[18,19] The Danish National Patient Registry has collected nationwide data on all nonpsychiatric hospital admissions since 1977, and since 1995 patients discharged from emergency departments and outpatient clinics have also been registered. The Danish National Board of Health maintains the registers and ensures the quality of the data. Participants with a discharge diagnosis or self-report of stroke before enrollment into the Nurses Cohort were excluded.

### Exposure Assessment

#### *Identification of Danish WTs*

A total of 8768 onshore WTs in operation at any time in Denmark from 1982 to 2013 (offshore turbines were excluded; n=510) were identified, using the administrative Master Data Register of WTs maintained by the Danish Energy Agency.[20] It is mandatory for all WT owners to report to the register, which contains geographic coordinates, date of grid connection, cancellation date for decommissioned turbines, and output for each Danish power-producing WT. Further details on the identification are provided in Data S1.

#### *WTN exposure data*

The noise contribution from WTs at each nurse's home was calculated according to the Nord2000 method.[21] Sound power levels from WTs were calculated for each address for

the periods each cohort member had lived at the specific address. The model takes into consideration continuous meteorological data for each WT for the years 1982 through 2013. The applied noise exposure modeling has been described in detail elsewhere.[21] In brief, WTN exposure was estimated for all the different present and historic addresses at which the nurses had lived using the Nord2000 noise propagation model, which has been validated for WT and previously detailed.[22,23] Outdoor A-weighted sound pressure levels ($LA_{eq}$)—a metric commonly used in health studies, were calculated at the most exposed façade of all buildings within a 6000-meter radius. WTN exposure was aggregated as follows: day ($L_d$; 07:00–19:00 hours), evening ($L_e$; 19:00–22:00 hours), night ($L_n$; 22:00–07:00 hours), expressed as $L_{den}$ (the overall weighted 24-hour noise level during the day, evening [+5 dB], and night [+10 dB]), and $L_{24\ h}$ (unweighted 24-hour average), as yearly averages. In this study we consider nurses who had at lived within a 6000-meter radius from at least 1 WT at some point of time in the period from January 1, 1982, to December 31, 2013, as exposed, and all others as unexposed to WTN.

### *Air pollution and noise from road traffic*

As previously described in detail,[24,25] we used the newly updated, high-resolution Danish air pollution dispersion modeling system (AirGIS) to estimate exposure to outdoor air pollution at the residence,[26] as annual mean levels of nitrogen oxide, road traffic–related pollutant, from 1982 to 2013. Road traffic noise at residential addresses of the nurses was estimated using the Nord2000 noise propagation model.

The input variables for the traffic noise model include the geocodes of the location, the height of apartments above street level, road lines with information on yearly average daily traffic, traffic composition and speed, road type (motorway, rural highway, road wider than 6 m, and other road), building polygons for all surrounding buildings (height of buildings, etc), and meteorology. Noise from road traffic was calculated at individual residential addresses for the period 1982 through 2013, as the equivalent continuous $LA_{eq}$ at the most exposed façade of the dwelling for the $L_d$, $L_e$, $L_n$, and $L_{den}$ as yearly averages.

## Statistical Analysis

We applied the Cox proportional hazards regression model to test the incidence of stroke as a function of WTN exposure *with age as the underlying time scale in all models*, ensuring comparison of individuals of the same age. Start of follow-up was at the age on the date of recruitment (April 1, 1993, or April 1, 1999), so nurses were considered at risk from recruitment, and end of follow-up was age at the date of first hospitalization discharge diagnosis of stroke, date of death, emigration, or December 31, 2013, whichever came first. Nurses with a stroke before enrollment were excluded from the analyses. The effect of WTN was evaluated in several steps: Model 1—a crude model, adjusted only for calendar year at recruitment into the cohort; Model 2—a main, fully adjusted model, additionally adjusted for a priori selected potential confounding variables and risk factors for stroke: smoking status (never, current, previous), smoking pack-years, alcohol consumption (g/week), physical activity (low, medium, high), the consumption of fruit (yes, no), avoidance of fatty meat consumption (yes, no), use of oral contraceptives, use of HRT, employment status (employed, unemployed, retired, other), and marital status (married, separated, divorced, unmarried, widow). The main analysis was performed on the cohort with complete information on all the covariates included in Model 2. The complete case analyses were considered valid, as we believe that the probability of being a complete case was independent of the outcome, given the covariates in Model 2.

We examined the following WTN exposures to assess chronic exposure using the 1-, 5-, and 11-year rolling mean during follow-up before diagnosis/censoring. In each rolling mean window, we considered $L_d$, $L_e$, $L_n$, $L_{den}$, and $L_{24\ h}$ separately. We used 2 categorical versions of WTN exposure: the first was our main exposure of interest with a cutoff at 20 dB, and the second was based on type-specific baseline quartiles, included for comparison with other studies. The cutoff at 20 dB was based on the rationale that in Denmark that low-frequency sound in the 10- to 160-Hz range is limited to an A-weighted level of 20 dB.[27] Furthermore, we modeled WTN as a continuous nonlinear (with a restricted cubic spline) and linear variable. The continuous variable reflects the relative increase in hazard for a 10-unit increase in exposure (10 dB) within the population of exposed nurses, and a 10-dB increase in noise level is equivalent to a subjective doubling in loudness.[28] WTN exposures were modeled as time-varying variables in all models. Further details of our statistical analysis are provided in Data S1. In brief, we carried out sensitivity analyses in separate models for possible mediators (body mass index, hypertension, diabetes mellitus, and socioeconomic status) and assessed potential effect modification (age, night-shift work, obesity, road traffic noise/nitrogen oxide traffic-related air pollution, and urbanicity index) and the competing effects of nonstroke death.

All effects are reported as cause-specific hazard ratios and 95% CIs. All analysis and graphical presentations were performed using the R statistical software 3.2.0 (with packages: survival, rms, Epi., maptools, OpenStreetMaps, and ggplot2).

Research was conducted in accordance with the principles of the Declaration of Helsinki, and the Danish Nurse Cohort study was approved by the Scientific Ethics Committee for Copenhagen and Frederiksberg; written informed consent was

**Table 1.** Characteristics of the Danish Nurse Cohort (n=23 912) at Baseline (1993 and 1999) according to Incident Stroke (n=1097) Status at End of Follow-Up (December 31, 2013)

| Baseline Characteristics Mean (SD) or n (%) | Total n=23 912 | Stroke Event (Yes) n=1097 | Stroke Event (No) n=22 815 |
|---|---|---|---|
| Age, y, mean (SD) | 53.3 (8.1) | 60.3 (9.2) | 52.9 (7.9) |
| Birth cohort | | | |
| <1930 | 5678 (23.7) | 626 (57.1) | 5052 (22.1) |
| 1930–1940 | 7192 (30.1) | 306 (27.8) | 6886 (30.2) |
| 1940–1950 | 5952 (24.9) | 120 (10.9) | 5832 (25.6) |
| ≥1950 | 5090 (21.3) | 45 (4.1) | 5045 (22.1) |
| BMI, kg/m$^2$, mean (SD) | 23.7 (3.5) | 23.8 (3.5) | 23.7 (3.5) |
| Underweight (BMI <18.5) | 586 (2.4) | 35 (3.2) | 551 (2.4) |
| Normal (BMI 18.5–25) | 16 323 (68.3) | 713 (65.0) | 15 610 (68.4) |
| Overweight (BMI 25–30) | 5408 (22.6) | 261 (23.8) | 5147 (22.6) |
| Obese (BMI >30) | 1350 (5.6) | 64 (5.8) | 1286 (5.6) |
| Missing | 245 (1.0) | 24 (2.2) | 221 (1.0) |
| Smoking | | | |
| Never | 8522 (35.6) | 325 (29.6) | 8197 (35.9) |
| Previous | 7205 (30.1) | 321 (29.3) | 68 864 (30.2) |
| Current | 8185 (34.2) | 451 (41.1) | 7734 (33.9) |
| Smoking pack-days, mean (SD)* | 16.3 (14.8) | 21.0 (19.3) | 16.0 (14.5) |
| Alcohol consumption | | | |
| Never | 3693 (15.4) | 231 (21.1) | 3462 (15.2) |
| Alcohol consumption† (g/wk), mean (SD) | 114.4 (126.2) | 105.2 (122.8) | 114.8 (126.3) |
| Physical activity | | | |
| Low | 1563 (6.5) | 90 (8.2) | 1473 (6.5) |
| Medium | 15 958 (66.7) | 769 (70.1) | 15 189 (66.6) |
| High | 6391 (26.7) | 238 (21.7) | 6153 (27.0) |
| Diet | | | |
| Regularly eat fruit | 16 252 (68.0) | 739 (67.4) | 15 513 (68.0) |
| Avoid fatty meat | 21 641 (90.5) | 963 (87.8) | 20 678 (90.6) |
| Hypertension | 3072 (12.8) | 251 (22.9) | 2821 (12.4) |
| Missing | 7 (0.03) | 0 (0.00) | 7 (0.03) |
| Diabetes mellitus | 280 (1.2) | 29 (2.6) | 251 (1.1) |
| Missing | 66 (0.3) | 2 (0.2) | 64 (0.3) |
| Use of hormone therapy | | | |
| Ever | 6559 (27.4) | 373 (34.0) | 6186 (27.1) |
| Use of oral contraceptives | | | |
| Ever | 14 036 (58.7) | 395 (36.0) | 13 641 (59.8) |
| Living in | | | |
| Urban area | 3541 (14.8) | 205 (18.7) | 3336 (14.6) |
| Rural | 9603 (40.1) | 381 (34.7) | 9222 (40.4) |
| Provincial | 10 145 (42.4) | 454 (41.1) | 9691 (42.5) |
| Missing | 623 (2.6) | 57 (5.2) | 566 (2.5) |

Continued

**Table 1.** Continued

| Baseline Characteristics Mean (SD) or n (%) | Total n=23 912 | Stroke Event (Yes) n=1097 | Stroke Event (No) n=22 815 |
|---|---|---|---|
| Marital status | | | |
| Married | 16 871 (70.6) | 647 (59.0) | 16 224 (71.1) |
| Separated | 392 (1.6) | 17 (1.5) | 375 (1.6) |
| Divorced | 2649 (11.1) | 142 (12.9) | 2507 (11.0) |
| Single | 2395 (10.0) | 156 (14.2) | 2239 (9.8) |
| Widow | 1609 (6.7) | 135 (12.3) | 1470 (6.4) |
| Employment status | | | |
| Employed | 18 722 (78.3) | 559 (51.0) | 18 163 (79.6) |
| Homemaker and others | 643 (2.7) | 22 (2.0) | 621 (2.5) |
| Retired | 4386 (18.3) | 509 (46.4) | 3877 (17.0) |
| Unemployed | 161 (0.7) | 7 (0.6) | 154 (0.7) |
| Night-shift work | | | |
| Day | 11 747 (49.1) | 338 (30.8) | 11 409 (50.0) |
| Evening | 1897 (7.9) | 70 (6.4) | 1828 (8.0) |
| Night | 1046 (4.4) | 56 (5.1) | 990 (4.3) |
| Rotating | 4115 (17.2) | 96 (8.7) | 4019 (17.6) |
| Missing | 5107 (21.4) | 537 (49.0) | 4570 (20.0) |
| Municipality annual income (DKK)‡, mean (SD) | 164.3432 (24.8) | 163.4 (24.4) | 164.3 (24.8) |
| Missing | 623 (2.6) | 2 (1.8) | 621 (2.7) |
| Annual air pollution, NOx ($\mu g/m^3$), mean (SD) | 19.2 (24.5) | 23.8 (31.1) | 19.0 (24.1) |
| Annual traffic noise, dB, mean (SD) | 52.8 (8.2) | 53.6 (7.7) | 52.7 (8.2) |
| WTN, dB, mean (SD)§ | 26.3 (6.78) | 26.2 (5.8) | 26.3 (6.7) |
| Unexposed | 21 427 (89.6) | 1005 (91.6) | 20 410 (89.5) |
| <21.5 dB | 622 (2.6) | 24 (2.2) | 598 (2.6) |
| 21.5–25.4 dB | 616 (2.6) | 18 (1.6) | 598 (2.6) |
| 25.4–29.9 dB | 619 (2.6) | 27 (2.5) | 592 (2.6) |
| >29.9 dB | 628 (2.6) | 23 (2.1) | 605 (2.7) |

BMI indicates body mass index; DKK, Danish crown; NOx, nitrogen oxide; SD, standard deviation; WTN, wind turbine noise.
*Among ever smokers.
†Among alcohol consumers.
‡Average annual gross income at the municipality level.
§Among nurses exposed to WTN.

obtained from all participants prior to enrollment. The present register-based study was approved by the Danish Data Protection Agency (J.nr: 2016-41-4792).

## Results

Of the total 28 731 recruited nurses in the Danish Nurse Cohort, we excluded 4819 because of death, missing geocodes, stroke prior to inclusion, or missing information on covariates, leaving 23 912 nurses for the final analyses.

The mean follow-up was 19.4 years, giving a total of 408 183 person-years of observations, during which 1097 nurses were registered with a hospital discharge for stroke, with an incidence rate of 2.7 new cases per 1000 person-years.

The nurses who were registered with stroke were over 7 years older on average; smoked more; consumed less alcohol; were less physically active; ate slightly more fatty meat; had higher rates of hypertension, diabetes mellitus, and HRT usage but lower rates of ever using oral contraceptives; tended to be retired, lived in areas with slightly lower incomes; were exposed to higher levels of nitrogen oxide traffic-related air pollution but around the same levels of annual weighted road traffic noise; and body mass index and fruit consumption at baseline than nurses who were not

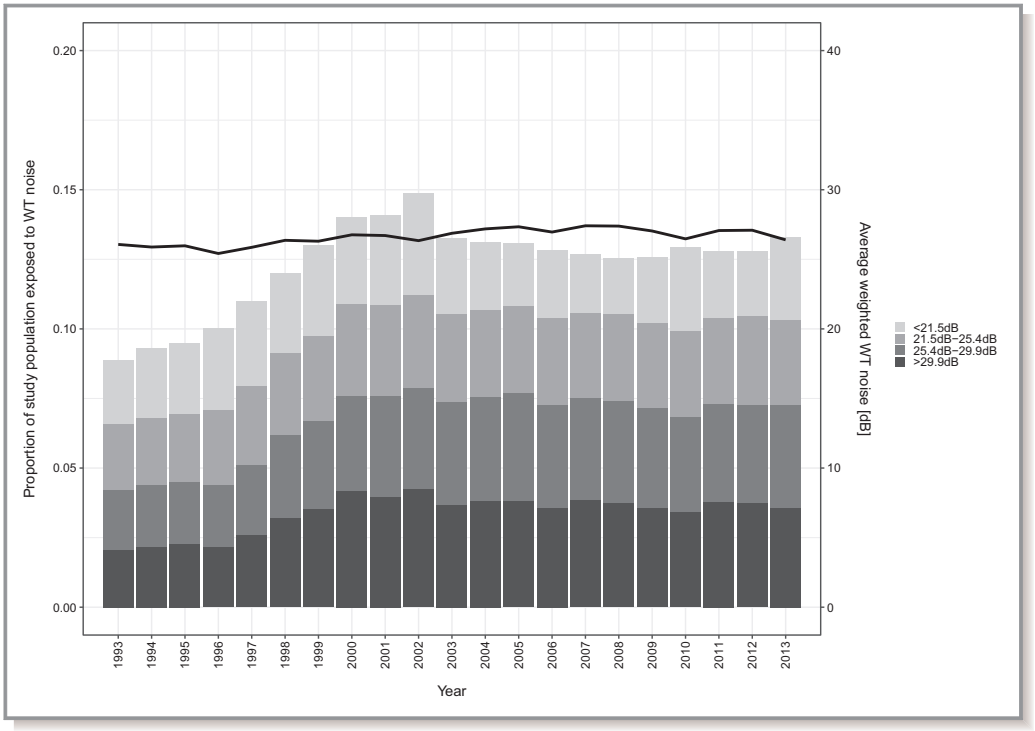


**Figure.** Average weighted $L_{den}$ for WTN exposure per year (right axis) and proportion of women living at WTN-exposed addresses (left axis). WTN indicates wind turbine noise.

registered with a hospital discharge diagnosis for stroke within the follow-up period. At baseline, the nurses registered with stroke were exposed to similar levels of WTN as those without stroke (Table 1).

Nurses from the Danish Nurse Cohort resided all around Denmark with wide geographic variation, with 14.8% residing in urban areas (population density ≥5220 people/km$^2$), 42.4% in provincial towns (180–5220 people/km$^2$), and 40.3% in rural areas (<180 people/km$^2$) at the cohort baseline, which corresponds closely to the distribution of the Danish population.

The estimated residential noise levels from WTs at baseline and distance to WT varied greatly, as did the proportion of women exposed throughout follow-up, with around 9% (n=1734) exposed in 1993, almost 15% (n=3943) in 2002, and 13% (n=3009) in 2013 (Figure). Mean (standard deviation) WTN levels among exposed nurses were 26.1 (6.4) dB in 1993, 26.3 (7.1) dB in 2002, and 26.4 (6.6) dB in 2013 (Figure).

Compared with 21 427 unexposed nurses at the cohort baseline, the 2485 exposed nurses were slightly younger, had higher body mass index, smoked less, were less physically active, had slightly higher rates of oral contraceptive use but lower HRT use, tended to still be working, lived in rural rather than urban areas, had slightly lower incomes, and were exposed to half the levels of nitrogen oxide traffic-related air pollution and lower annual levels of weighted road traffic noise but were similar in regards to hypertension, avoiding consumption of fatty meats, fruit consumption, and diabetes mellitus rates (Table S1).

We detected no nonlinear relationships between weighted WTN and stroke incidence (Figure S1). Table 2 shows the associations between weighted WTN and stroke (n=1097) (hospitalization) incidence among 23 912 Danish Nurse Cohort participants. We found no association between WTN and stroke incidence: the adjusted hazard ratios and 95% CIs for the 11-, 5-, and 1-year running mean residential $L_{den}$ exposures preceding hospitalization, comparing nurses with ≥20 dB(A) to nurses exposed to levels <20 dB(A) were 1.09 (0.90–1.31), 1.08 (0.89–1.31), and 1.08 (0.89–1.32), respectively. Results with $L_{den}$ were comparable with WTN exposure at $L_n$, $L_d$, $L_e$, and $L_{24\ h}$ (unweighted daily average) (Table 2). Likewise, when considering the same association according to exposure quartiles (Table S2), we found no significant associations.

## Identification of Confounders and Effect Modifiers

Only minor attenuation by the included a priori selected confounders in the fully adjusted model was observed (Table 2).

There was no evidence of effect by any of the assessed variables in the sensitivity analyses, with no marked deviation

from the main Model 2 (not shown in tables). We detected significant effect modification of the association between WTN with stroke by urbanicity, showing the strongest positive associations for nurses living in provincial areas, and negative association in rural and urban areas. No effect modification by age, obesity, road traffic noise, or air pollution was observed (Table S3).

## Competing Risk by Nonstroke Death

The number of competing risk events within the cohort during follow-up was high (nonstroke death, n=3568), compared with the outcome of interest (stroke, n=1097); however, there was no indication of competing risk in Model 2 (main model), and nonstroke death did not potentially mask the association of interest in this study.

## Discussion

In this nationwide, prospective cohort study of Danish female nurses, we found no evidence to support a causal relationship between long-term exposure to WTN and stroke incidence, within the exposure windows considered (11-, 5- and 1-year).

Our results are in line with another recent Danish nationwide study that explored the relationship between WTN exposure and stroke incidence reporting no consistent associations with outdoor WTN or indoor low-frequency WTN and all incidence rate ratios were null or inverse and nonsignificant. The results of the present comprehensive study along with that recent study with a representative distribution of present and historical addresses around Denmark provide novel insight into this relationship. The present results also support another recently published paper reporting no associations between WTN exposure and incidence of myocardial infarction.[4,29] In public health perspective this may help reassure concerned citizens and ease the ongoing concern regarding the potential cardiovascular-related health effects of WTN exposure.

Long-term exposure to transportation noise has been associated with higher risk for cardiovascular disease including myocardial infarction and stroke.[2,3,30,31] These same associations are not observed with WTN, which can be attributed to many factors: first, WTN is generally much lower than traffic noise, for example, in Denmark there is no legislation limiting noise emitted for road traffic, and it is estimated that almost one third of all domestic dwellings are exposed to levels of road traffic that exceed 58 dB(A), while legislation prohibits WTN at levels exceeding of 44 dB(A) (wind speed of 8 m/s) and 42 dB(A) (wind speed of 6 m/s) for dwellings in open country.[32] Second, WTN is characterized by a more rhythmic modulation of sound than traffic sources, and seems to cause more annoyance and sleep disturbance than road traffic noise (and other environmental noise sources) at similar noise levels.[33,34] Third, WTs are typically located in rural areas in which background noise levels and sensitivity thresholds to noise may be lower. Finally, road traffic noise is ubiquitous, affecting everyone, and a source of particulate or gaseous oxidative stressors (relevant for cardiovascular end points), while WTN is nonubiquitous, predominantly a rural exposure, with around 800 000 homes (≈12%) located within a 6000-meter radius of at least 1 wind turbine in Denmark in 2016.

We benefited from objective assessment of stroke incidence based on high-quality Danish registries with near 100% coverage,[18,35] as well as detailed information on stroke risk factors. This assessment implies minimal possibility of recall and information bias and no selection bias. We furthermore benefited from the state-of-the-art high-resolution validated exposure models for WT and road traffic noise[21–23] as well as air pollution,[36] which were based on geocodes and also accounted for all address changes and meteorological conditions, as well as the size and the type of WT. Overall associations support no association with most CIs spanning 1, and the few HRs above 1 are thought to be chance findings or attributable to residual confounding and not true effects. This is also supported by the lack of linear dose-response relationships.

In the present study, the WTN levels were relatively low. Only 25% of nurses exposed to WTN, those living within a 6000-meter radius of ≥1 WT, were exposed to levels over 29.9 dB(A) throughout follow-up, which corresponds to around 3% of all included nurses. The majority of the included nurses (>80%) had never lived in proximity to a WT. Thus, only a small fraction of the Danish population is exposed to WTN levels that are considered dangerous for health. According to the World Health Organization, it is not plausible that noise levels ≤30 dB(A) would cause sleep disturbances, and that only modest health effects would be expected ≤40 dB(A).[37] In the most recent environmental guidelines for the European Union, the World Health Organization conditionally recommends that WT $L_{den}$ levels should be reduced to below 45 dB (A),[38] much in line with the limits set by the Danish Environmental Protection Agency of 44 dB(A) (wind speed of 8 m/s) and 42 dB(A) (wind speed of 6 m/s) for dwellings in open country.[32] This may imply that the noise levels in our study may not have induced intermediates (hypertension, sleep disturbance, etc) previously reported to be on the causal pathway from noise exposure to stroke,[39–42] and direct auditory effects leading to stroke at these levels are not expected.[41] These levels of WTN are also substantially lower than road traffic noise levels within the same cohort, which were >50 dB (A) on average, noting that a 20-dB(A) difference between these 2 sources of noise levels is perceived as around 4 times the loudness, due to the logarithmic scale of sound.[28]

**Table 2.** Association Between Weighted WTN ($L_{den}$, $L_d$, $L_e$, $L_n$, and $L_{24\ h}$) and Stroke Incidence (n=1097) Among 23 912 Danish Nurse Cohort Participants for Exposure Above and Below 20 dB(A), Considering the 1-, 5- and 11-Year Rolling Means Before Diagnosis/Censoring

| WTN [dB(A)] | Person-Years | N Cases | Incidence Rate per 1000 Person-Years | Model 1* HR (95% CI) | Model 2† HR (95% CI) |
|---|---|---|---|---|---|
| $L_{den}$ | | | | | |
| $L_{den}$ 11-year | | | | | |
| <20 | 362 451 | 976 | 2.7 | 1 | 1 |
| ≥20 | 45 731 | 121 | 2.6 | 1.06 (0.87–1.28) | 1.09 (0.90–1.31) |
| Linear‡ | | 1097 | | 0.98 (0.81–1.18) | 0.99 (0.81–1.20) |
| $L_{den}$ 5-year | | | | | |
| <20 | 362 547 | 980 | 2.7 | 1 | 1 |
| ≥20 | 45 636 | 117 | 2.6 | 1.05 (0.87–1.27) | 1.08 (0.89–1.31) |
| Linear‡ | | 1097 | | 1.07 (0.86–1.35) | 1.09 (0.86–1.37) |
| $L_{den}$ 1-year | | | | | |
| <20 | 364 939 | 984 | 2.7 | 1 | 1 |
| ≥20 | 44 244 | 113 | 2.6 | 1.06 (0.87–1.28) | 1.08 (0.89–1.32) |
| Linear‡ | | 1097 | | 1.21 (0.92–1.60) | 1.23 (0.93–1.62) |
| $L_d$ | | | | | |
| $L_d$ 11-year | | | | | |
| <20 | 385 834 | 1043 | 2.7 | 1 | 1 |
| ≥20 | 22 349 | 54 | 2.4 | 0.97 (0.74–1.28) | 1.00 (0.76–1.32) |
| Linear‡ | | 1097 | | 0.99 (0.81–1.20) | 1.00 (0.82–1.21) |
| $L_d$ 5-year | | | | | |
| <20 | 384 533 | 1031 | 2.7 | 1 | 1 |
| ≥20 | 23 649 | 66 | 2.8 | 1.17 (0.91–1.50) | 1.20 (0.94–1.54) |
| Linear‡ | | 1097 | | 1.09 (0.87–1.36) | 1.10 (0.88–1.38) |
| $L_d$ 1-year | | | | | |
| <20 | 384 346 | 1031 | 2.7 | 1 | 1 |
| ≥20 | 23 837 | 66 | 2.8 | 1.18 (0.92–1.51) | 1.21 (0.94–1.55) |
| Linear‡ | | 1097 | | 1.22 (0.93–1.61) | 1.24 (0.94–1.63) |
| $L_e$ | | | | | |
| $L_e$ 11-year | | | | | |
| <20 | 386 146 | 1043 | 2.7 | 1 | 1 |
| ≥20 | 22 037 | 54 | 2.5 | 0.98 (0.75–1.29) | 1.01 (0.77–1.33) |
| Linear‡ | | 1097 | | 0.99 (0.81–1.20) | 1.00 (0.82–1.21) |
| $L_e$ 5-year | | | | | |
| <20 | 384 647 | 1032 | 2.7 | 1 | 1 |
| ≥20 | 23 535 | 65 | 2.8 | 1.15 (0.89–1.47) | 1.18 (0.92–1.52) |
| Linear‡ | | 1097 | | 1.08 (0.86–1.36) | 1.09 (0.87–1.38) |
| $L_e$ 1-year | | | | | |
| <20 | 384 327 | 1031 | 2.7 | 1 | 1 |
| ≥20 | 23 856 | 66 | 2.8 | 1.17 (0.91–1.50) | 1.20 (0.93–1.54) |
| Linear‡ | | 1097 | | 1.22 (0.92–1.61) | 1.23 (0.93–1.63) |

Continued

**Table 2.** Continued

| WTN [dB(A)] | Person-Years | N Cases | Incidence Rate per 1000 Person-Years | Model 1* HR (95% CI) | Model 2† HR (95% CI) |
|---|---|---|---|---|---|
| $L_n$ | | | | | |
| $L_n$ 11-year | | | | | |
| <20 | 387 151 | 1045 | 2.7 | 1 | 1 |
| ≥20 | 21 031 | 52 | 2.5 | 0.99 (0.75–1.31) | 1.02 (0.77–1.35) |
| Linear‡ | | 1097 | | 0.97 (0.80–1.18) | 0.98 (0.81–1.19) |
| $L_n$ 5-year | | | | | |
| <20 | 385 721 | 1034 | 2.7 | 1 | 1 |
| ≥20 | 22 462 | 63 | 2.8 | 1.17 (0.90–1.50) | 1.20 (0.93–1.55) |
| Linear‡ | | 1097 | | 1.07 (0.85–1.34) | 1.08 (0.86–1.36) |
| $L_n$ 1-year | | | | | |
| <20 | 385 284 | 1032 | 2.7 | 1 | 1 |
| ≥20 | 22 899 | 65 | 2.8 | 1.20 (0.94–1.55) | 1.24 (0.96–1.59) |
| Linear‡ | | 1097 | | 1.21 (0.92–1.60) | 1.22 (0.93–1.62) |
| $L_{24\ h}$ | | | | | |
| $L_{24\ h}$ 11-year | | | | | |
| <20 | 386 364 | 1044 | 2.7 | 1 | 1 |
| ≥20 | 21 819 | 53 | 2.4 | 0.98 (0.74–1.29) | 1.01 (0.76–1.33) |
| Linear‡ | | 1097 | | 0.98 (0.81–1.19) | 1.00 (0.82–1.21) |
| $L_{24\ h}$ 5-year | | | | | |
| <20 | 385 003 | 1033 | 2.7 | 1 | 1 |
| ≥20 | 23 179 | 64 | 2.8 | 1.15 (0.89–1.48) | 1.18 (0.92–1.53) |
| Linear‡ | | 1097 | | 1.08 (0.86–1.36) | 1.09 (0.87–1.37) |
| $L_{24\ h}$ 1-year | | | | | |
| <20 | 384 679 | 1033 | 2.7 | 1 | 1 |
| ≥20 | 23 504 | 64 | 2.7 | 1.15 (0.89–1.48) | 1.19 (0.92–1.53) |
| Linear‡ | | 1097 | | 1.22 (0.92–1.61) | 1.23 (0.93–1.63) |

HR indicates hazard ratio.
*Adjusted for age (underlying timeline) and calendar year at entrance into the cohort.
†Main model, as for Model 1+smoking (status, pack-years), alcohol consumption, physical activity, avoid fatty meat consumption, fruit consumption, use of oral contraceptives, use of hormone therapy, marital status, employment status.
‡Linear trend per 10 dB(A).

The main limitation in the present study is the exposure misclassification in the modeled WTN concentrations, as these are only proxies of personal exposure and we did not have a measure of indoor levels of WTN. Also, although our estimation of WTN exposure is based on complete residential histories, we cannot account for exposures via temporary migration to other destinations, at work in other regions in Denmark, or while overseas in areas with either higher or lower noise exposures. Finally, the A-weighted nature of our estimates is not informative about any peaking characteristics of the WTN throughout follow-up, and there may have been peaks we did not address.

Another major weakness of our study is the small number of stroke cases exposed to high levels of WTN, limiting the power to detect effects in this range of noise exposure. Furthermore, we had no available information on personal sensitivity to noise, levels of annoyance, or sleep quality, which have all been reported to be on the casual pathway between noise exposure and health effects.[5,6,43–45] However, these self-reports may have introduced bias, as they include highly motivated persons with possible negative attitudes to WTs, which have repeatedly been reported to play an important role as the underlying cause of reported health and sleep problems.[7,34,46,47] In our study, it was not feasible

to consider all noise sources including noise from neighbors, bedroom snoring, aircraft, railways, and ventilation. Another weakness is that we lacked data on personal and household income, important determinants of socioeconomic status. Information on confounding and effect-modifying variables were collected at cohort baseline, and we acknowledge that these may have changed throughout the 20-year average follow-up time. Finally, we consider only women and are thus unable to account for effects in men or eventual differences in effect according to sex.

The results of this study infer no association between long-term exposure to WTN and stroke in women above age 44.

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## Disclosures

None.

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# Supplemental Material

**Data S1.**

## Supplemental Methods

Study population - The Danish Nurse Cohort

The study was based in the Danish Nurse Cohort [1] which was inspired by the American Nurses' Health Study to investigate the health effects of hormone replacement therapy (HRT) in a European population. In 1993, the cohort was initiated by sending a questionnaire to 23,170 female members of the Danish Nurse Organization who were at least 44 years old at the time. The Danish Nurse Organization includes 95% of all nurses in Denmark. In total, 19,898 (86%) nurses replied, and the cohort was reinvestigated in 1999 when firstly 10,534 new nurses (who had reached the age of 44 years in the period 1993-99) were invited of which 8,344 responded) and secondly 2,231 non-responders from 1993 were re-invited of which 489 responded. The questionnaire included questions on socio-economic and working conditions, parents' occupation, weight and height, lifestyle (diet, smoking, alcohol consumption and leisure time physical activity), self-reported health, family history of cardiovascular disease, use of oral contraceptives and HRT. In the present study we used the earliest baseline information from 1993 (19,898) or 1999 (8,833) for 28,731 of nurses.

Since establishment of the Central Population Register in 1968 [2, 3], all citizens of Denmark have been given a unique personal identification number, which allows accurate linkage between registers. The cohort members were linked to the Central Population Register [2, 3] to obtain the nurses vital status information at 31st December 2013 (active, date of death/emigration). Using the unique personal identification number of the cohort members, all residential histories were traced in the Central Population Register between 1982 and 2013. Each residential address contained a unique identification code composed of a municipality-, road- and house number code. The dates

the persons had moved to and from each address were noted. The addresses were then linked to a database of all official addresses and their geographical coordinates in Denmark.

Identification of outcome - National Patient Register

The endpoint was incidence for stroke (International Classification of Disease (ICD) 10: D161, D163 and ICD 8:431.0, 431.9, 432.0, 432.9, 433.09, 433.99, 434.09, 436.0 and 436.9), defined as first-ever hospital contact (emergency, in- or outpatient) for stroke, identified in the Danish National Patient Registry [4, 5]. The Danish National Patient Registry has collected nationwide data on all non-psychiatric hospital admissions since 1977, and since 1995, patients discharged from emergency departments and outpatient clinics have also been registered. The Danish National Board of Health maintains the registers and assures the quality of the data. Participants with a discharge diagnosis or self-report of stroke before enrolment into the Nurses Cohort were excluded.

Exposure assessment

*Identification of Danish WTs:* 8768 on-shore WTs in operation at any time in Denmark from 1982 to 2013 (off-shore turbines were excluded, n = 510) were identified, using the administrative Master Data Register of Wind Turbines maintained by the Danish Energy Agency [6]. It is mandatory for all WT owners to report to the register, which contains geographical coordinates, date of grid connection, cancelation date for decommissioned turbines, and output for each Danish power producing WT. Each of the turbines was classified into one of 99 noise spectra classes detailing the noise spectrum from 10 Hz to 10,000 Hz in thirds of octaves for wind speeds from 4 to 25 m/s, based on individual WT data including height, model, type and operational settings (when relevant). These noise classes were formed from existing measurements of sound power for Danish WTs [7]. At each WT location, wind speed and direction at hub height was estimated, using mesoscale model simulations [8, 9]. Temperature and relative humidity at 2m height as well as the atmospheric stability were also estimated from these simulations.

*WTN exposure data:* Each of the nurses' homes was identified and geocoded. The noise contribution at each nurses' homes from WTs was calculated according Nord2000 method [7]. Sound power levels from WTs were calculated for each address in the periods each cohort member had lived at the specific address. The model takes into consideration, continuous meteorological data for each WT throughout the years 1982-2013. The applied noise exposure modelling has been described in detail elsewhere [7]. In brief, WTN exposure was estimated for the all the different present and historic addresses the nurses had lived in using the Nord2000 noise propagation model which has been validated for WT and previously detailed [10, 11]. Outdoor A-weighted sound pressure level ($LA_{eq}$) – a metric commonly used in health studies was calculated at the most exposed façade of all buildings within a 6000 m radius. WTN exposure was aggregated as follows: day ($L_d$; 07:00–19:00h), evening ($L_e$; 19:00–22:00h), night ($L_n$; 22:00–07:00h), expressed as $L_{den}$ (the overall weighted 24-hr noise level during the day, evening (+5dB) and night (+10 dB)), and $L_{24}$ (unweighted 24-hr average), as yearly averages. Geographical coordinates were obtained for 99.9% of all the addresses. In this study we consider nurses who had at lived within a 6000m radius from at least one WT at some point of time in the period from 1.1.1982 to 31.12.2013 as exposed, and all others as unexposed to WTN.

*Air pollution and noise from road traffic*: As previously described in detail [12, 13], we used the newly updated, high-resolution Danish air pollution dispersion modeling system (AirGIS) to estimate exposure to outdoor air pollution at the residence[14], as annual mean levels of nitrogen oxide ($NO_x$), road traffic related pollutant, from 1982-2013. Road traffic noise at residential addresses of the nurses was estimated using the Nord2000 noise propagation model. The input variables for the traffic noise model include the geocodes of the location, the height of apartments above street level, road lines with information on yearly average daily traffic, traffic composition and speed, road type (motorway, rural highway, road wider than 6m, and other road), building polygons for all

surrounding buildings (height of buildings, etc.), and meteorology. Noise from road traffic was calculated at individual residential addresses for the period 1982-2013, as the equivalent continuous $LA_{eq}$ at the most exposed façade of the dwelling for the $L_d$, $L_e$, $L_n$, and $L_{den}$ as yearly averages.

Statistical analysis

We applied the Cox proportional hazards regression model to test the incidence of stroke as a function of WTN exposure *with age as the underlying time scale in all models*, ensuring comparison of individuals of the same age. Start of follow-up was at the age on the date of recruitment (1st April 1993 or 1st April 1999), so nurses were considered at risk from recruitment, and end of follow-up was age at the date of first hospitalization discharge diagnosis of stroke, date of death, emigration or 31st December 2013, whichever came first. Nurses with a stroke before enrollment were excluded from the analyses. The effect of WTN was evaluated in several steps: Model 1) A crude model, adjusted only for calendar year at recruitment into the cohort; Model 2) A main, fully adjusted model, additionally adjusted for *a-priori* selected potential confounding variables: smoking status (never, current, previous), smoking pack-years, alcohol consumption (g/week), physical activity (low, medium, high), the consumption of fruit (yes, no), avoidance of fatty meat consumption (yes, no), use of oral contraceptives, use of HRT, employment status (employed, unemployed, retired, other) and marital status (married, separated, divorced, unmarried, widow). The main analysis was performed on the cohort with complete information on all the covariates included in Model 2.

We examined the following WTN exposures to assess chronic exposure using the 1-, 5- and 11-year rolling mean during follow-up prior to diagnosis/censoring. In each rolling mean window, we considered $L_d$, $L_e$, $L_n$, $L_{den}$ and $L_{24h}$ separately. We used two categorical versions of WTN exposure: the first with a cut off at 20dB and the second was based on type-specific baseline quartiles.

Furthermore, we modelled WTN as a continuous nonlinear (with a restricted cubic spline) and linear variable.

To avoid enforcement of linearity between being exposed to WTN and not being exposed, two variables were used in these models; a binary variable distinguishing unexposed from exposed (0/1) and a continuous variable with the actual exposure for those exposed and the median exposure level for unexposed subjects. The continuous variable reflects the relative increase in hazard for ten units increase in exposure (10 dB) within the population of exposed nurses, and a 10 dB increase in noise level is equivalent to a subjective doubling in loudness [15]. Furthermore, we estimated HRs for the categorical versions of WTN exposures with a cut-off at 20 dB, based on the rationale that in Denmark, low-frequency sound in the 10–160 Hz range is limited to an A-weighted level of 20 dB [16]. WTN exposures were modelled as time-varying variables in all models.

We carried out sensitivity models to assess possible mediators of an association between WTN and stroke in four additional separate models. Model 3) as for model 2, further adjusted for Body Mass Index (BMI); Model 4) as for model 2, further adjusted for self-reported hypertension at baseline; Model 5) as for model 2, further adjusted for self-reported diabetes at baseline and Model 6) as for model 2, further adjusted for average gross income at the municipality at baseline, which we used as a proxy for socio-economic status. Continuous variables, year, smoking pack-years, alcohol consumption, BMI, and average gross income at the municipality were modelled with restricted cubic splines. Noise estimates and traffic air $NO_x$ pollution were available for every year of follow-up and all potential confounding and effect mediating variables were available at baseline.

The potential effect modification of the association between WTN amongst exposed nurses and stroke incidence by age, night shift work, obesity, road traffic noise/$NO_x$ traffic related air pollution and urbanicity index were examined by introducing interaction terms to the main model (model 2) with WTN as a linear variable and tested by the likelihood ratio test.

The cohort consists of elderly nurses (> 44 at the recruitment, and > 58 years old at the end of follow-up in 2013), thus the effect of non-stroke death as a competing risk was also investigated as a function of WTN to assess whether time to stroke in our main models was precluded by death.

All effects are reported as cause-specific hazard ratios (HRs) and 95% confidence intervals (CIs). All analysis and graphical presentations were performed using the R statistical software 3.2.0 (with packages: survival, rms, Epi., maptools, OpenStreetMaps, ggplot2).

Spearman correlation between metrics of WTN and traffic noise and air pollution were estimated and these were not correlated (r=0.14).

Research was conducted in accordance with principles of the Declaration of Helsinki and the Danish Nurses Cohort study was approved by the Scientific Ethics Committee for Copenhagen and Frederiksberg and written informed consent was obtained from all participants prior to enrollment. The present register based study was approved by the Danish Data Protection Agency (J.nr: 2016-41-4792). By Danish Law, ethical approval and informed consent are not required for entirely register-based studies.

**Table S1. Characteristics of the Danish Nurse Cohort (n = 23,912) at baseline (1993 and 1999) by baseline exposure.**

| Baseline Characteristics | Unexposed<br>n = 21,427 | Exposed (yes)<br>n = 2,485 |
|---|---|---|
| Stroke, n (%) | 1005 | 92 |
| Person-years of follow-up, n | 366,471 | 41,711 |
| Incidence rate per 1,000 person-years | 2.7 | 2.2 |
| Age, years, mean (SD) | 53.4 (8.2) | 51.8 (7.2) |
| Birth cohort | | |
| < 1930, n (%) | 5,214 (24.3) | 464 (18.7) |
| 1930-1940, n (%) | 6,557 (30.6) | 635 (25.6) |
| 1940-1950, n (%) | 5,260 (24.5) | 692 (27.8) |
| ≥1950, n (%) | 4,396 (20.5) | 694 (27.9) |
| BMI, kg/m$^2$, mean (SD) | 23.7 (3.5) | 24.0 (3.6) |
| Underweight (BMI <18.5 kg/m$^2$), n (%) | 533 (2.5) | 53 (2.1) |
| Normal (BMI 18.5-25 kg/m$^2$), n (%) | 14,688 (68.5) | 1,635 (65.8) |
| Overweight (BMI 25-30 kg/m$^2$), n (%) | 4,800 (22.4) | 608 (24.5) |
| Obese (BMI >30 kg/m$^2$), n (%) | 1,186 (5.5) | 164 (6.6) |
| Missing, n (%) | 220 (1.0) | 25 (1.0) |
| Smoking | | |
| Never smoked, n (%) | 7,533 (35.2) | 989 (39.8) |
| Previously smoked, n (%) | 6,486 (30.3) | 719 (28.9) |
| Current smoker, n (%) | 7,408 (34.6) | 777 (31.3) |
| Smoking pack--days, mean (SD)* | 16.4 (14.9) | 15.3 (13.5) |
| Alcohol consumption | | |
| Never consumes alcohol, n (%) | 3,315 (15.5) | 378 (15.2) |
| Alcohol consumption† (g/week), mean (SD) | 115.6 (126.4) | 104.2 (123.5) |
| Physical activity | | |
| Low physical activity, n (%) | 1,417 (6.6) | 146 (5.9) |
| Medium physical activity, n (%) | 14,418 (67.3) | 1,540 (62.0) |
| High physical activity, n (%) | 5,592 (26.1) | 799 (32.2) |
| Diet | | |
| Regularly eat fruit, n (%) | 14,593 (68.1) | 1,659 (66.8) |
| Avoid fatty meat, n (%) | 19,425 (90.7) | 2,216 (89.2) |
| Hypertension, n (%) | 2,775 (13.0) | 297 (12.0) |
| Missing, n (%) | 7 (0.03) | 0 (0.00) |
| Diabetes, n (%) | 243 (1.1) | 37 (1.5) |
| Missing, n (%) | 55 (0.3) | 11 (0.4) |
| Use of hormone therapy | | |
| Ever, n (%) | 5,956 (27.8) | 603 (24.3) |
| Use of oral contraceptives | | |
| Ever, n (%) | 12,464 (58.2) | 1,572 (63.3) |
| Living in | | |
| Urban Area, n (%) | 3,492 (16.3) | 49 (2.0) |
| Rural, n (%) | 7,808 (36.4) | 1,795 (72.2) |
| Provincial, n (%) | 9,542 (44.5) | 603 (24.3) |
| Missing, n (%) | 585 (2.8) | 38 (1.5) |
| Marital status | | |
| Married, n (%) | 14,856 (69.3) | 2,015 (81.1) |
| Separated, n (%) | 364 (1.7) | 28 (1.1) |
| Divorced, n (%) | 2,465 (11.5) | 184 (7.4) |
| Single, n (%) | 2,259 (10.5) | 136 (5.5) |
| Widow, n (%) | 1,483 (6.9) | 122 (4.9) |
| Employment status | | |

| | | |
|---|---|---|
| Employed, n (%) | 16,686 (77.9) | 2,036 (81.9) |
| Homemaker and others, n (%) | 554 (2.6) | 89 (3.5) |
| Retired, n (%) | 4,043 (18.9) | 343 (13.8) |
| Unemployed, n (%) | 144 (0.7) | 17 (0.7) |
| Night shift work | | |
| Day | 10,474 (48.9) | 1,273 (51.2) |
| Evening | 1,686 (7.9) | 211 (8.5) |
| Night | 933 (4.4) | 113 (4.5) |
| Rotating | 3,659 (17.1) | 456 (18.4) |
| Missing, n, (%) | 4,675 (21.8) | 456 (18.4) |
| Municipality annual income (DKK)‡, mean (SD) | 165.05 (25.77) | 157.567 (11.76) |
| Missing n, (%) | 585 (2.4) | 38 (1.6) |
| Annual Air Pollution, NOx (µg/$m^3$), mean(SD) | 20.2 (25.5) | 10.8 (9.8) |
| Annual traffic noise, dB, (mean, SD) | 53.3 (7.9) | 48.3 (9.2) |
| Wind-turbine noise, dB, (mean, SD)§ | - | 26.25 (6.61) |
| Unexposed, n (%) | 21,427 (100) | 0 (0.0) |
| < 21.5 dB, n (%) | 0 (0.0) | 622 (25.0) |
| 21.5-25.4 dB, n (%) | 0 (0.0) | 616 (24.8) |
| 25.4-29.9 dB, n (%) | 0 (0.0) | 619 (24.9) |
| > 29.9 dB, n (%) | 0 (0.0) | 628 (25.3) |
| | | |

SD: Standard deviation

BMI: body mass index

DKK: Danish crown

*among ever smokers

†among alcohol consumers

‡average annual gross income at the municipality level

§among Nurses exposed to WTN

**Table S2. Association between long-term wind-turbine noise exposure ($L_{den}$, $L_{day}$ $L_{evening}$, $L_{night}$, and $L_{24-h}$) and stroke incidence (n = 1,097) among 23,912 Danish Nurse Cohort participants, considering 1-, 5- and 11-yrs rolling means preceding diagnosis/censoring according to quartiles for our crude and main adjusted models.**

| | Person-years (PY) | $N_{cases}$ | Incidence Rate per 1,000 PY | Model 1† HR (95% CI) | Model 2‡ HR (95% CI) |
|---|---|---|---|---|---|
| **1. Lden** | | | | | |
| **$L_{den}$ 11-year rolling mean** | | | | | |
| Unexposed | 341357 | 921 | 2.7 | 1 (ref) | 1 (ref) |
| < 21.5 dB(A) | 26874 | 67 | 2.4 | 1.03 (0.80-1.32) | 1.05 (0.81-1.34) |
| 21.5-25.4 dB(A) | 14086 | 43 | 3.1 | 1.22 (0.90-1.65) | 1.24 (0.92-1.69) |
| 25.4-29.9 dB(A) | 13006 | 34 | 2.6 | 1.01 (0.72-1.43) | 1.04 (0.74-1.47) |
| > 29.9 dB(A) | 12858 | 32 | 2.5 | 1.04 (0.73-1.48) | 1.08 (0.76-1.54) |
| **$L_{den}$ 5-year rolling mean** | | | | | |
| Unexposed | 350294 | 948 | 2.7 | 1 (ref) | 1 (ref) |
| < 21.5 dB(A) | 17504 | 42 | 2.4 | 0.99 (0.72-1.34) | 1.01 (0.74-1.37) |
| 21.5-25.4 dB(A) | 13113 | 27 | 2.1 | 0.84 (0.57-1.23) | 0.85 (0.58-1.25) |
| 25.4-29.9 dB(A) | 13483 | 45 | 3.3 | 1.32 (0.98-1.78) | 1.36 (1.01-1.84) |
| > 29.9 dB(A) | 13787 | 35 | 2.5 | 1.08 (0.77-1.52) | 1.12 (0.80-1.57) |
| **$L_{den}$ 1-year rolling mean** | | | | | |
| Unexposed | 358208 | 973 | 2.7 | 1 (ref) | 1 (ref) |
| < 21.5 dB(A) | 10447 | 20 | 1.9 | 0.78 (0.50-1.22) | 0.80 (0.51-1.25) |
| 21.5-25.4 dB(A) | 12057 | 26 | 2.2 | 0.88 (0.59-1.30) | 0.89 (0.60-1.31) |
| 25.4-29.9 dB(A) | 13266 | 42 | 3.2 | 1.26 (0.92-1.71) | 1.29 (0.94-1.75) |
| > 29.9 dB(A) | 14205 | 36 | 2.5 | 1.10 (0.79-1.53) | 1.14 (0.81-1.59) |
| **2. Lday** | | | | | |
| **$L_{day}$ 11-year rolling mean** | | | | | |
| Unexposed | 341358 | 921 | 2.7 | 1 (ref) | 1 (ref) |
| <15.1 dB (A) | 27252 | 70 | 2.6 | 1.05 (0.83-1.34) | 1.07 (0.84-1.37) |
| 15.1-19.0 dB(A) | 13800 | 40 | 2.9 | 1.15 (0.84-1.58) | 1.17 (0.85-1.61) |
| 19.0-23.6 dB(A) | 13191 | 35 | 2.7 | 1.04 (0.74-1.46) | 1.07 (0.76-1.50) |
| >23.6 dB(A) | 12583 | 31 | 2.5 | 1.03 (0.72-1.48) | 1.07 (0.75-1.53) |
| **$L_{day}$ 5-year rolling mean** | | | | | |
| Unexposed | 350297 | 948 | 2.7 | 1 (ref) | 1 (ref) |
| <15.1 dB (A) | 17918 | 44 | 2.4 | 1.01 (0.75-1.37) | 1.03 (0.76-1.39) |
| 15.1-19.0 dB(A) | 12940 | 28 | 2.1 | 0.87 (0.60-1.27) | 0.89 (0.61-1.29) |
| 19.0-23.6 dB(A) | 13649 | 43 | 3.3 | 1.25 (0.92-1.70) | 1.29 (0.95-1.76) |
| >23.6 dB(A) | 13378 | 34 | 2.5 | 1.09 (0.77-1.54) | 1.13 (0.80-1.59) |
| **$L_{day}$ 1-year rolling mean** | | | | | |
| Unexposed | 358211 | 973 | 2.7 | 1 (ref) | 1 (ref) |
| <15.1 dB (A) | 10929 | 24 | 1.9 | 0.89 (0.59-1.34) | 0.91 (0.61-1.37) |
| 15.1-19.0 dB(A) | 11992 | 25 | 2.2 | 0.84 (0.56-1.25) | 0.85 (0.57-1.26) |
| 19.0-23.6 dB(A) | 13307 | 40 | 3.2 | 1.21 (0.88-1.66) | 1.24 (0.90-1.70) |

| | | | | | |
|---|---|---|---|---|---|
| >23.6 dB(A) | 13743 | 35 | 2.5 | 1.11 (0.79-1.55) | 1.14 (0.82-1.61) |
| **3. Levening** | | | | | |
| **$L_{evening}$ 11-year rolling mean** | | | | | |
| Unexposed | 341559 | 921 | 2.7 | 1 (ref) | 1 (ref) |
| <15.0 dB(A) | 26903 | 66 | 2.5 | 1.01 (0.79-1.30) | 1.03 (0.80-1.33) |
| 15.0-18.9 dB(A) | 14130 | 43 | 3.0 | 1.21 (0.89-1.64) | 1.23 (0.91-1.68) |
| 18.9-23.5 dB(A) | 13286 | 35 | 2.6 | 1.02 (0.73-1.43) | 1.05 (0.75-1.47) |
| >23.5 dB(A) | 12505 | 32 | 2.6 | 1.07 (0.75-1.53) | 1.11 (0.78-1.58) |
| **$L_{evening}$ 5-year rolling mean** | | | | | |
| Unexposed | 350298 | 948 | 2.7 | 1 (ref) | 1 (ref) |
| <15.0 dB(A) | 17475 | 40 | 2.9 | 0.94 (0.69-1.30) | 0.96 (0.70-1.32) |
| 15.0-18.9 dB(A) | 13196 | 29 | 2.2 | 0.89 (0.62-1.29) | 0.91 (0.63-1.31) |
| 18.9-23.5 dB(A) | 13749 | 47 | 3.4 | 1.35 (1.00-1.80) | 1.39 (1.03-1.86) |
| >23.5 dB(A) | 13465 | 33 | 2.5 | 1.05 (0.74-1.49) | 1.09 (0.77-1.54) |
| **$L_{evening}$ 1-year rolling mean** | | | | | |
| Unexposed | 358212 | 973 | 2.7 | 1 (ref) | 1 (ref) |
| <15.0 dB(A) | 10411 | 21 | 2.0 | 0.82 (0.53-1.27) | 0.84 (0.55-1.30) |
| 15.0-18.9 dB(A) | 12120 | 23 | 1.9 | 0.78 (0.51-1.18) | 0.79 (0.52-1.19) |
| 18.9-23.5 dB(A) | 13525 | 44 | 3.3 | 1.28 (0.94-1.73) | 1.31 (0.97-1.78) |
| >23.5 dB(A) | 13915 | 36 | 2.6 | 1.12 (0.81-1.57) | 1.16 (0.83-1.62) |
| **4. Lnight** | | | | | |
| **$L_{night}$ 11-year rolling mean** | | | | | |
| Unexposed | 341361 | 921 | 2.7 | 1 (ref) | 1 (ref) |
| <14.7 dB(A) | 26972 | 67 | 2.5 | 1.02 (0.80-1.31) | 1.04 (0.81-1.34) |
| 14.7-18.6 dB(A) | 14063 | 43 | 3.1 | 1.22 (0.90-1.66) | 1.25 (0.92-1.70) |
| 18.6-23.1 dB(A) | 12989 | 34 | 2.6 | 1.01 (0.72-1.43) | 1.04 (0.74-1.47) |
| >23.1 dB(A) | 12798 | 32 | 2.5 | 1.05 (0.73-1.49) | 1.08 (0.76-1.54) |
| **$L_{night}$ 5-year rolling mean** | | | | | |
| Unexposed | 350301 | 948 | 2.7 | 1 (ref) | 1 (ref) |
| <14.7 dB(A) | 17564 | 42 | 2.4 | 0.98 (0.72-1.34) | 1.00 (0.73-1.37) |
| 14.7-18.6 dB(A) | 13132 | 26 | 2.0 | 0.81 (0.55-1.19) | 0.82 (0.55-1.21) |
| 18.6-23.1 dB(A) | 13454 | 46 | 3.4 | 1.35 (1.01-1.82) | 1.39 (1.03-1.87) |
| >23.1 dB(A) | 13732 | 35 | 2.5 | 1.09 (0.78-1.53) | 1.13 (0.80-1.58) |
| **$L_{night}$ 1-year rolling mean** | | | | | |
| Unexposed | 358215 | 973 | 2.7 | 1 (ref) | 1 (ref) |
| <14.7 dB(A) | 10520 | 20 | 1.9 | 0.78 (0.50-1.21) | 0.80 (0.51-1.24) |
| 14.7-18.6 dB(A) | 12062 | 26 | 2.2 | 0.88 (0.59-1.29) | 0.89 (0.60-1.31) |
| 18.6-23.1 dB(A) | 13234 | 42 | 3.2 | 1.26 (0.92-1.71) | 1.29 (0.95-1.76) |
| >23.1 dB(A) | 14152 | 36 | 2.5 | 1.10 (0.79-1.54) | 1.14 (0.82-1.59) |
| **5. L24-h** | | | | | |
| **$L_{24h}$ 11-year rolling mean** | | | | | |
| Unexposed | 341357 | 921 | 2.7 | 1 (ref) | 1 (ref) |
| <14.9 dB(A) | 26974 | 67 | 2.5 | 1.02 (0.80-1.31) | 1.04 (0.81-1.34) |
| 14.9-18.9 dB(A) | 14301 | 43 | 3.0 | 1.19 (0.88-1.62) | 1.22 (0.90-1.66) |
| 18.9-23.4 dB(A) | 12882 | 36 | 2.8 | 1.08 (0.78-1.51) | 1.11 (0.80-1.56) |
| >23.4 dB(A) | 12669 | 30 | 2.4 | 0.99 (0.69-1.43) | 1.03 (0.71-1.48) |

| | | | | | |
|---|---|---|---|---|---|
| **$L_{24h}$ 5-year rolling mean** | | | | | |
| Unexposed | 350294 | 948 | 2.7 | 1 (ref) | 1 (ref) |
| <14.9 dB(A) | 17578 | 42 | 2.4 | 0.98 (0.72-1.34) | 1.00 (0.73-1.36) |
| 14.9-18.9 dB(A) | 13394 | 30 | 2.2 | 0.91 (0.63-1.31) | 0.92 (0.64-1.33) |
| 18.9-23.4 dB(A) | 13369 | 42 | 3.1 | 1.24 (0.91-1.70) | 1.28 (0.94-1.75) |
| >23.4 dB(A) | 13548 | 35 | 2.6 | 1.11 (0.79-1.55) | 1.14 (0.82-1.61) |
| **$L_{24h}$ 1-year rolling mean** | | | | | |
| Unexposed | 358208 | 973 | 2.7 | 1 (ref) | 1 (ref) |
| <14.9 dB(A) | 10570 | 21 | 2.0 | 0.81 (0.52-1.25) | 0.83 (0.54-1.28) |
| 14.9-18.9 dB(A) | 12337 | 27 | 2.2 | 0.89 (0.61-1.30) | 0.90 (0.61-1.32) |
| 18.9-23.4 dB(A) | 13136 | 40 | 3.0 | 1.21 (0.88-1.66) | 1.24 (0.90-1.70) |
| >23.4 dB(A) | 13931 | 36 | 2.6 | 1.12 (0.81-1.57) | 1.16 (0.83-1.62) |
| | | | | | |

HR: Hazard Ratio; CI: Confidence Intervals;

† Adjusted for age (underlying timeline) and calendar year at entrance into the cohort

‡ Main model, as for model 1† + smoking (status, pack-years), alcohol consumption, physical activity, avoid fatty meat consumption, fruit consumption, use of oral contraceptives, use of hormone therapy, marital status, employment status.

**Table S3. Modification of association[†] within population of exposed Nurses between incidence of stroke (n = 1097) and WTN (11-year rolling mean per 10 dB(A)) by baseline characteristics and co-morbid conditions among 23,912 female participants in the Danish Nurse Cohort.**

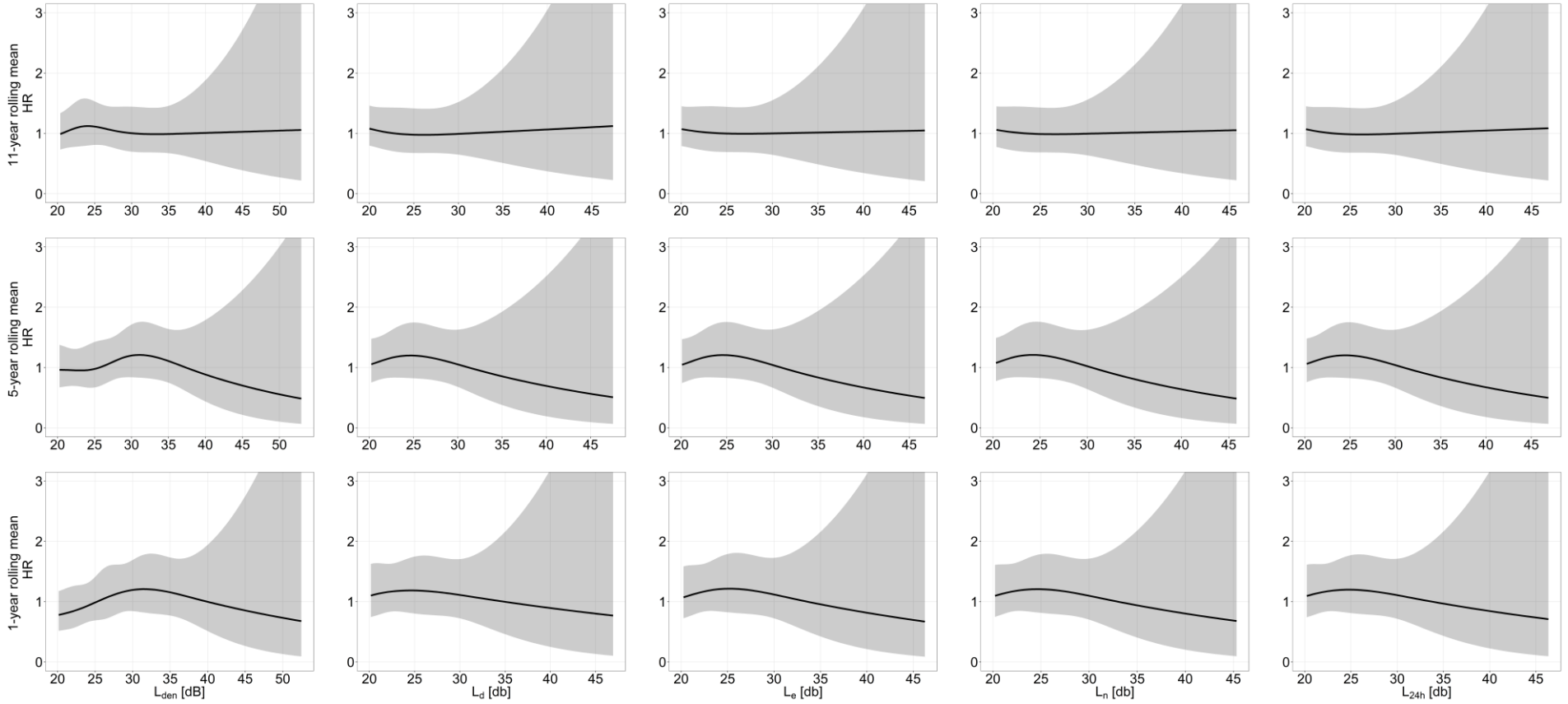
| Covariate | | N (cases) | HR (95%CI) | $p^{‡}$ |
|---|---|---|---|---|
| Age | <60 years | 34 | 0.88 (0.58-1.33) | *0.54* |
| | ≥60 years | 142 | 1.02 (0.82-1.27) | |
| BMI | < 25 kg/m$^2$ | 109 | 0.95 (0.74-1.21) | *0.41* |
| | ≥ 25 kg/m$^2$ | 65 | 1.05 (0.77-1.45) | |
| Traffic noise (dB) | < 53.7 dB | 110 | 1.04 (0.82-1.33) | *0.82* |
| | ≥ 53.7 | 63 | 0.92 (0.66-1.27) | |
| Traffic air pollution (NOx) | < 15.2 µg/m$^3$ | 107 | 1.01 (0.79-1.30) | *0.71* |
| | ≥ 15.2 µg/m$^3$ | 62 | 1.01 (0.73-1.39) | |
| Night shift | Night only | 15 | 1.40 (0.69-2.81) | *0.17* |
| | Day, evening, rotating | 91 | 1.08 (0.83-1.41) | |
| Level of Urbanization | Urban | 7 | 0.26 (0.12-0.56) | *0.004** |
| | Rural | 123 | 0.97 (0.77-1.22) | |
| | Provincial | 44 | 1.32 (0.89-1.96) | |

HR: Hazard Ratio; CI: Confidence Interval;

[†]Adjusted for age, calendar year at entrance into the cohort, smoking (status, pack-years), alcohol consumption, physical activity, avoid fatty meat consumption, fruit consumption, use of oral contraceptives, use of hormone therapy, marital status, employment status. However, with no adjustment for the modification variable.

[‡]From likelihood ratio test for interaction, test of the null hypothesis that linear trends are identical.

**Figure S1. Exposure-response (HR (hazard ratio) filled lines; 95% CIs indicated by dashed lines) between stroke (n=1097) and 11, 5, and 1-y WT ($L_{den}$, $L_d$, $L_e$, $L_n$ and $L_{24h}$) noise exposure at residences from 1982 onwards, based on fully adjusted main model 2. The reported HR (hazard risk) is based on unexposed nurses as reference.**



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