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Long-Term Exposure to Transportation Noise in Relation to Development of Obesity—a Cohort Study

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Background: Exposure to transportation noise is widespread and has been associated with obesity in some studies. However, the evidence from longitudinal studies is limited and little is known about effects of combined exposure to different noise sources.

Objectives: The aim of this longitudinal study was to estimate the association between exposure to noise from road traffic, railways, or aircraft and the development of obesity markers.

Methods: We assessed individual long-term exposure to road traffic, railway, and aircraft noise based on residential histories in a cohort of 5,184 men and women from Stockholm County. Noise levels were estimated at the most exposed façade of each dwelling. Waist circumference, weight, and height were measured at recruitment and after an average of 8.9 y of follow-up. Extensive information on potential confounders was available from repeated questionnaires and registers.

Results: Waist circumference increased 0.04 cm/y (95% CI: 0.02, 0.06) and 0.16 cm/y (95% CI: 0.14, 0.17) per 10 dB L_{den} in relation to road traffic and aircraft noise, respectively. No corresponding association was seen for railway noise. Weight gain was only related to aircraft noise exposure. A similar pattern occurred for incidence rate ratios (IRRs) of central obesity and overweight. The IRR of central obesity increased from 1.22 (95% CI: 1.08, 1.39) in those exposed to only one source of transportation noise to 2.26 (95% CI: 1.55, 3.29) among those exposed to all three sources.

Conclusion: Our results link transportation noise exposure to development of obesity and suggest that combined exposure from different sources may be particularly harmful. https://doi.org/10.1289/EHP1910

Introduction

Large parts of the population are exposed to elevated levels of noise, particularly in urban areas. Road traffic is a dominating source but both railway and aircraft noise contribute in certain areas. Exposure to transportation noise may result in annoyance and sleep disturbance (Basner et al. 2014; Miedema and Oudshoorn 2001; Miedema and Vos 2007) as well as in cardiovascular disease (Münzel et al. 2016). Recently, it has been suggested that markers of obesity, such as waist circumference and body mass index (BMI), may be associated with exposure to transportation noise in adults (Christensen et al. 2015a, 2015b; Eriksson et al. 2014; Oftedal et al. 2015; Pyko et al. 2015), but the evidence is not wholly consistent. Only one of the studies focusing on road traffic noise was longitudinal and used self-reported data on weight and waist circumference, which are prone to bias. In addition, there are studies on obesity in relation to residence near major roads (Li et al. 2016) and air pollution exposure (Jerrett et al. 2014), which indicates that it is important to assess both air pollution and noise exposure to elucidate causal associations when exposure from road traffic is focused.

It has been hypothesized that the relation between environmental noise and cardiovascular disease may involve sleep disturbances and psychological stress (Münzel et al. 2016) and the same mechanisms may also be relevant for metabolic diseases such as obesity and type 2 diabetes. Sleep deprivation may lead to dysregulation of appetite-regulating hormones, such as leptin and ghrelin, and contribute to overweight (Chaput et al. 2007; Van Cauter et al. 2008). Furthermore, noise may act as a stressor and lead to the elevation of cortisol levels, thereby promoting central fat deposition and impaired glucose regulation (Björntorp 1997; Rosmond 2003). For example, it has been shown that subjects living near airports have elevated saliva cortisol levels related to noise exposure (Selander et al. 2009a). Combined exposure to several stressors, such as different noise sources or work stress may be particularly harmful (Pyko et al. 2015; Selander et al. 2013; Tétreault et al. 2013). However, data on interactions between exposure to several stressors in relation to development of obesity are limited as well as on the combined effects of noise and air pollution exposure.

In a previous publication we reported results based on a cross-sectional analysis of transportation noise exposure and markers of obesity in a cohort from Stockholm County (Pyko et al. 2015). The present study is based on the same study population, but has a longitudinal design, and uses a newly developed methodology enabling more precise assessment of long-term exposure to transportation noise from different sources as well as objective outcome data. The aim was to estimate the association between exposure to transportation noise and development of obesity markers. As a secondary objective, we assessed the role of combined exposure to multiple sources of transportation noise, including road traffic, railways, and aircraft as well as interactions with air pollution exposure.

Methods

The present study was based on the Stockholm Diabetes Prevention Program cohort, which has been described in detail previously (Eriksson et al. 2008). Briefly, the program was conducted between 1992 and 2006 in Stockholm County with the primary

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aim to study risk factors for type 2 diabetes as well as to implement and evaluate methods for prevention. Participants were recruited between 1992 and 1998 from five municipalities in Stockholm County (Upplands Bro, Upplands Väsby, Sigtuna, Värmdö, and Tyresö). These municipalities mainly include suburban and semirural areas.

By an enrichment procedure in the original design of the study, approximately half of the participants had a family history of diabetes (52%), that is, at least one first-degree relative (mother, father, or sibling) or two second-degree relatives (grandparent, uncle, or aunt) with diabetes. Those with family history were matched on age and sex with individuals who did not have a family history of diabetes. A total of 3,162 (69.8%) men and 4,946 (70.3%) women accepted the invitation. After the baseline survey and medical examination 34 men and 125 women were excluded due to diabetes diagnosis or other medical reasons. Thus, 7,949 participants 35–56 y of age formed the diabetes-free baseline sample. Some members of the baseline sample died or moved out of Stockholm County during follow-up ($n = 838$), and all remaining 7,111 participants were invited to a new survey 8 to 10 y after the baseline survey (see Figure S1). A total of 5,712 persons (corresponding to 80% of those invited) took part in the follow-up survey and medical examination.

At both baseline and follow-up investigations, participants filled out questionnaires and trained nurses measured weight, height, and waist circumference. The questionnaires covered health status as well as lifestyle habits such as smoking, alcohol intake, and physical activity during leisure time, dietary habits, psychological distress, shift work, insomnia, and job strain. Moreover, the follow-up questionnaire enquired about noise annoyance and noise sensitivity.

We obtained information on residential address history for the participants from the Swedish Population Register through the Swedish Taxation Authority. The residential address history included information on each address where the participants had lived starting from 1990, with precise times of address changes during follow-up.

The study was conducted in accordance with the Helsinki Declaration and approved by the Regional Ethics Review Board at Karolinska Institutet. All participants gave informed consent to the original study which also applied to the present analyses.

Noise Exposure Assessment

To assess long-term individual road transportation noise exposure, a noise database was constructed for Stockholm County to represent the period 1990–2010. The database contains information from several national, regional, and local authorities and includes 3-dimensional terrain data as well as information on ground surface, road net, daily traffic flows, speed limits, and percentage of heavy vehicles. Data were available on the road traffic situation every fifth year (1990, 1995, 2000, 2005, and 2010). To calculate noise levels, we developed and used a modification of the Nordic prediction method for road traffic (Bendtsen 1999; Nielsen 1997). The Nordic method uses traffic flow, distribution of heavy and light vehicles, speed, and pavement type to calculate the noise emission from each road link. The noise level at a receiving point is then calculated by summing the contribution of every road link using a propagation correction based on distance between road and receiver, presence of screening objects such as noise barriers or buildings, terrain shape, and whether the ground is acoustically soft or hard. Meteorological effects are included to some extent, but vegetation is not considered other than as soft ground. We modified the Nordic method for dense urban areas where possible reflection and shielding are taken into account by a ground space index based on building density (Salomons and Pont 2012). Thus, instead of the detailed information on buildings a typical reflection and shielding scenario based on building density was applied. The higher building density and the longer the distance from a source to a receiver, the higher the probability of both reflections and screening by the buildings. This modification led to decreased computational time as well as to avoiding geometrical errors such as the receiver positions being placed inside buildings instead of being exactly on the façade. Our method was validated against the full Nordic prediction method modeled with SoundPLAN (version 6.3; SoundPLAN GmbH) and showed coherent estimates. A more detailed description of the simplified noise modeling methodology instead of using detailed information on buildings is provided elsewhere (Ögren and Barregard 2016). Information on road traffic noise barriers was not included because of insufficient data on year of construction.

Using the residential address history, we estimated noise levels due to road traffic at the most exposed façade for all relevant addresses. The equivalent continuous A-weighted sound pressure level (L_{Aeq}) was calculated, and assuming a 24-h distribution of road traffic as 75%/20%/5% for day, evening, and night, respectively, we expressed noise levels as L_{den}, which corresponds to the equivalent level with a penalty of 3.4 dB considering noise during evening (+5 dB) and night (+10 dB) (Murphy and King 2010). The modeled noise levels were interpolated between the years with road traffic noise estimates. For each participant, we calculated the time-weighted average noise exposure during follow-up taking into account all addresses in Stockholm County where the subject had lived and considering the duration of residence at each address.

For railway noise, we used parts of the same database (3-dimensional terrain data, ground surface, residential history) as for road traffic noise supplemented with relevant information on the railway net, such as speed limits, train counts, and train types, as well as the exact 24-h distribution for different parts of the railway net for the years 1990–2012. Information on railway noise barriers was not taken into account because we generally lacked data on year of construction. As for road traffic, we applied the typical reflection and shielding scenario based on building density instead of detailed information on buildings. Railway noise levels were expressed as L_{den} with time-weighted exposure during the follow-up computed in a similar way as for road traffic noise.

With assistance from Swedavia, which operates the two main airports (Arlanda and Bromma) in Stockholm County, we obtained noise contour data of annual levels around the airports for the years 1995, 2000, 2005, and 2010. We assumed the same noise level in 1990 as in 1995 because there were no major structural changes in the airports between these years. The noise contour data ranged from 45 dB L_{den} near Arlanda and from 40 dB L_{den} near Bromma and were combined with the residential address history data. The annual noise levels at each address point were interpolated between the years with data during the follow-up period. Time-weighted exposure to aircraft noise was computed in relation to residential time at each address.

Outcome Definitions

All measurements of weight and height as well as of waist circumference were performed by trained nurses according to a standard protocol during the baseline and follow-up investigations. Height and weight were measured with the participant standing without shoes and were rounded to the nearest 0.5 cm or 100 g, respectively. Waist circumference was measured with the participant in lying face up, midway between the lower costal margin and iliac crest. Anthropometric markers of obesity were defined according to the WHO criteria for the European population. BMI was calculated as the weight divided by the squared height (kilograms per meter squared) with a cutoff at ≥ 25 to define overweight. Sex-specific cutoff values for central obesity were applied for waist circumference: ≥ 88 cm for women and ≥ 102 cm for men (WHO 2008). We used weight gain in the analyses based on continuous outcomes because it is more easily interpretable than changes in BMI as well as for comparability with previous evidence.

Men and women were investigated during partly different time periods, leading to differences in follow-up time with means of 10.2 and 8.0 y, respectively. Moreover, the follow-up time varied from 6.1 to 11.0 y between individual participants. Therefore, the change in weight and waist circumference was calculated by dividing weight gain and waist circumference increase from baseline to follow-up with the individual follow-up time in years (kilograms per year and centimeters per year, respectively).

Covariates

The covariates evaluated as confounders were identified based on a literature search and by development of a directed acyclic graph (DAG) with DAGitty.net software (see Figure S2) (Textor et al. 2011). We used the DAG to select a set of confounders for assessment of the direct effect of transportation noise on the development of obesity. Information on age, sex, physical activity, dietary habits, psychological distress, family history of diabetes, occupational status, shift work, educational level, marital status, alcohol consumption, smoking status, sleep disturbance, dietary habits, psychological distress, and job strain was obtained from the baseline questionnaire. Data on noise sensitivity and annoyance by transportation noise were obtained from the follow-up questionnaire. Furthermore, information on household mean income in small geographical areas with an average population of 1,000–2,000 subjects was obtained from registers held by Statistics Sweden to adjust for contextual confounding.

Dietary habits were assessed using "recommended" and "non-recommended" food scores (Pyko et al. 2015). In recommended foods we included consumption of low-fat dairy products, wholemeal or hard bread, fruits, vegetables (score $+1$ if consumed at least two to three times per week), and porridge ($+1$ if consumed at least one to three times per month). Among the non-recommended foods we included consumption of high-fat dairy products, white bread (score $+1$ if consumed at least two to three times per week), fast foods ($+1$ if consumed at least one to three times per month), cakes and sweets ($+1$ if consumed at least once a week). Summarized, the two scores for recommended and non-recommended foods ranged from 0 to 15 and 0 to 16, respectively. We considered more than 8 of 15 in recommended food score as a healthy diet indicator and more than 8 of 16 in non-recommended food score as an unhealthy diet indicator.

We assessed job strain based on the Swedish version of the Karasek and Theorell demand–decision latitude questionnaire (Agardh et al. 2003). Baseline indices for work-related demands and decision latitude were created and categorized in tertiles, and the highest tertile of demand together with the lowest tertile of decision latitude defined job strain. An index was also created for psychological distress that was assessed from baseline questions on anxiety, apathy, depression, fatigue, and insomnia (Eriksson et al. 2008).

Based on the individual residential history, we calculated time-weighted exposure to nitrogen oxides (NO_x) from road traffic for each participant during follow-up using a dispersion modeling methodology developed to assess long-term source-specific exposure in Stockholm County (Bellander et al. 2001; Gruzieva et al. 2012).

Further covariates used in the adjusted models included physical activity during leisure time (sedentary: exercise less than 2 h per week/moderate: exercise at least 2 h per week/regular: exercise at least 30 min one to two times per week/frequent regular: exercise at least 30 min three times or more per week), alcohol consumption (daily/weekly/seldom/never), education (primary school/upper secondary school/university), smoking status (never/former/current), employment status (gainfully employed/unemployed/retired), psychological distress (yes/no), job strain (yes/no), and shift work (yes/no).

Statistical Methods

We tested differences in background characteristics related to road traffic noise exposure with Pearson chi-squared tests for categorical variables and one-way ANOVA for continuous variables. Pearson correlations were used to describe relationships between different transportation noise sources and road traffic–related NO_x.

Linear regression models were used to analyze associations between transportation noise exposure and weight and waist circumference changes with the estimation of regression coefficients and 95% confidence intervals (CIs). Homoscedastic variance was checked by residual plots, and normality was assessed by normal probability plots of the residuals. The analyses were performed for continuous transportation noise exposures, and associations are presented for an increment of 10 dB L_{den}. To examine associations between transportation noise exposure and incidence of central obesity as well as overweight, we used Poisson regression models estimating incidence rate ratios (IRRs) and 95% CIs. In each analysis, those with the outcome at baseline were excluded. We approximated person-time with the length of follow-up and this was specified as an offset parameter in the model.

Additionally, we tested the assumption of linearity between transportation noise and weight as well as waist circumference changes. First, we performed analyses with a categorical exposure variable (<45, 45–49, 50–54, and ≥ 55 dB L_{den}) by inserting it in the linear model. Second, we performed restricted cubic splines analyses with 3 knots determined by Harell's method (knots placed at the 10th, 50, and 90 percentiles). Also, we assessed the effect of combined exposure to multiple noise sources by creating dummy variables, indicating subjects exposed to none, one, two, or three transportation noise sources ≥ 45 dB L_{den}. We performed Cuzick nonparametric trend tests for the ranks across exposure groups to estimate *p*-values for trend.

Results are mainly presented based on two adjustment models. First, a crude model is used with adjustment for only sex and age (35/40/45/50/55 y of age). Second, a fully adjusted model is presented with additional adjustment for dietary habits, physical activity during leisure time, alcohol consumption, education level, physical activity, smoking status, psychological distress, job strain, and shift work.

Effect modification of the association between road traffic noise and development of obesity measures by characteristics from baseline (sex, education, BMI, and waist circumference vs. railway noise and diabetes heredity) as well as follow-up (age, noise annoyance, noise sensitivity, and air pollution) were evaluated by introducing interaction terms into the models and by using *F*-test statistics.

We performed sensitivity analyses to investigate how the association between road traffic noise exposure and the IRR for central obesity was affected by restriction of the population to those who did not change their residential address, those were exposed to only road traffic noise, or those without diabetes heredity. Moreover, results of additional adjustment for other transportation noise sources, baseline waist circumference, municipality, and contextual confounding (area based mean income) are also presented. In particular, the effects were evaluated of additional adjustments for air pollution from local traffic using NO_x as the indicator.

Hypothesis testing for all analyses was based on two-tailed rejection regions and *p*-values less than 5% were considered statistically significant, except for the interaction terms, where 10% was used as significance level. Statistical analyses were performed using Stata/SE (version 13.1; StataCorp, College Station, TX); and spatial manipulation of data and exposure assessment were performed in QGIS (version 2.10.1; QGIS Development Team).

Results

Of the 5,712 persons participating in the follow-up survey 82 (1.4%) were excluded because of missing exposure data; 94 (1.6%) because of missing data on anthropometric variables at baseline or follow-up; and 352 (6.1%) because of missing data on the covariates included in the main model. Following these exclusions, a study population of 5,184 (91%) individuals remained with complete information and a mean follow-up time of 8.9 y.

Of those included in the study 2,739 (53%) were not exposed to a noise level of ≥45 dB L_{den} from any transportation noise source; 1,901 (37%) participants were exposed to one of three transportation noise sources at this level or higher; 487 (9%) to two sources of transportation noise, and 57 (1%) to all three sources ≥45 dB L_{den} (see Figure S3).

Women reported road traffic noise exposure ≥45 dB L_{den} more often than men because some of them were recruited from one municipality (Upplands-Väsby) that was not included in the recruitment of men (Table 1). Furthermore, participants with higher noise exposure had lower education and socioeconomic status, were less physically active during leisure time, had more job strain and psychological distress, and reported that they were less noise sensitive. Furthermore, those exposed were more annoyed by road traffic noise and more often exposed to railway and aircraft noise.

The mean follow-up time was 8.0 y in women and 10.2 y in men and mean weight gain was 0.28 kg/y (SD 0.72) among women and 0.32 kg/y (SD 0.56) among men (see Table S1). Mean waist circumference increase differed among women and men and was 0.64 cm/y (SD 0.80) and 0.33 cm/y (SD 0.64), respectively. Excluding those with overweight at baseline, 2,560 (49%), the cumulative incidence of overweight in the remaining 2,624 participants during follow-up was 25% and 36% for women and men, respectively. In contrast, the cumulative incidence of central obesity in those 4,386 without central obesity at baseline was 23% and 16% in women and men, respectively.

Table 2 presents associations between transportation noise exposures from different sources and continuous outcomes. In the fully adjusted model, we observed an association between road traffic noise and waist circumference increase of 0.04 cm/y (95% CI: 0.02, 0.06) per 10 dB L_{den}. For aircraft noise, the waist circumference increase was 0.16 cm/y (95% CI: 0.14, 0.17) per 10 dB L_{den}. No clear association was observed between railway noise and waist circumference increase. Weight gain was associated with aircraft noise, and changed 0.03 kg/y (95% CI: 0.01, 0.04) per 10 dB L_{den}, but not with road or railway traffic noise exposure.

Both categorical and restricted cubic splines analyses suggested nonlinearity in the association between road traffic noise exposure and waist circumference increase (Table 2, Figure 1). It is suggested that there might be a threshold in the exposure–response relation at around 45–50 dB L_{den}. However, departure from linearity was not statistically significant (*p*-value of

Table 1. Characteristics of the study cohort from Stockholm County in relation to road traffic noise exposure during follow-up [*n* (%)].

Individual characteristics[a]	Time-weighted average road traffic exposure <45 dB L_{den} ($n = 3,457$)	≥45 dB L_{den} ($n = 1,727$)	*p*-Value
Women	1,914 (55)	1,069 (62)	0.007
Age (y)			0.050
35–39	333 (10)	141 (8)	
40–44	659 (19)	316 (18)	
45–49	1,196 (35)	573 (33)	
50–55	1,269 (37)	697 (40)	
Socioeconomic status			0.019
Low	889 (26)	483 (28)	
Medium	704 (20)	390 (23)	
High	1,609 (47)	746 (43)	
Other	166 (5)	67 (4)	
Occupational status			0.185
Gainfully employed	3,162 (91)	1,573 (91)	
Unemployed	217 (6)	101 (6)	
Retired	78 (2)	53 (3)	
Shift work	329 (10)	181 (10)	0.272
Smoking status			0.275
Current	812 (23)	439 (25)	
Former	1,274 (37)	631 (37)	
Never	1,371 (40)	657 (38)	
Physical activity during leisure time[b]			0.012
Sedentary	329 (10)	206 (12)	
Moderate	1,853 (54)	909 (53)	
Regular	986 (29)	497 (29)	
Frequent regular	289 (8)	115 (7)	
Alcohol consumption			0.336
Daily	153 (4)	73 (4)	
Weekly	2,241 (65)	1,131 (65)	
Seldom	949 (27)	451 (26)	
Never	114 (3)	72 (4)	
Education level			0.021
Primary school	1,017 (29)	565 (33)	
Secondary school	1,340 (39)	666 (39)	
University degree or higher	1,100 (32)	496 (29)	
Job strain[c]	381 (11)	221 (13)	0.060
Psychological distress[d]	696 (20)	410 (24)	0.003
Noise sensitivity[e]			0.036
Less sensitive than others	637 (18)	357 (21)	
Same sensitivity as others	2,441 (71)	1,210 (70)	
More sensitive that others	378 (11)	158 (9)	
Noise annoyance from road traffic[e]			<0.001
Seldom/never	3,191 (92)	1,263 (73)	
Few times per month	134 (4)	187 (11)	
Few times per week	79 (2)	149 (9)	
Each day	46 (1)	123 (7)	
Healthy diet[f]	318 (9)	175 (10)	0.280
Unhealthy diet[f]	2,167 (63)	1,030 (60)	0.034
Diabetes heredity[g]	1,776 (51)	924 (54)	0.148
Railway noise over 45 dB L_{den}[h]	213 (6)	183 (11)	<0.001
Aircraft noise over 45 dB L_{den}[h]	578 (17)	345 (20)	0.004

[a]Characteristics are from the baseline investigation unless stated otherwise. Number of participants in each group, percentages in parenthesis and *p*-values are reported.
[b]Physical activity during leisure time is defined as sedentary (regular exercise less than 2 h per week), moderate (regular exercise at least 2 h per week), regular (regular exercise at least 30 min one to two times per week), frequent regular (at least 30 min three times or more per week).
[c]Job strain is defined as a combination of the highest tertile of demand together with the lowest tertile of decision latitude at work.
[d]Psychological distress is assessed as the highest quartile of a summed index based on questions on anxiety, apathy, depression, fatigue, and insomnia.
[e]From follow-up investigation.
[f]More than 8 of 15 in recommended food score and 8 of 16 in non-recommended food score (see "Methods" section).
[g]Family history of diabetes defined if participants had at least one first-degree relative (parent or sibling) with diabetes or at least two second-degree relatives (grandparents, aunts, uncles) with diabetes.
[h]Time-weighted average during follow-up period.

Table 2. Noise exposure from different transportation noise sources during follow-up for the study cohort from Stockholm County in relation to waist circumference increase and weight gain.

Exposure[a]	No. total	Waist circumference increase (cm/y) Model 1[b] β (95% CI)	Waist circumference increase (cm/y) Model 2[c] β (95% CI)	Weight gain (kg/y) Model 1[b] β (95% CI)	Weight gain (kg/y) Model 2[c] β (95% CI)
Road traffic noise					
Continuous per 10 dB L_{den}		0.04 (0.02, 0.07)	0.04 (0.02, 0.06)	0.01 (−0.006, 0.03)	0.01 (−0.009, 0.03)
Categorical, dB L_{den}					
<45	3,457	0 Referent	0 Referent	0 Referent	0 Referent
45–49	958	−0.04 (−0.09, 0.01)	−0.05 (−0.10, 0.003)	−0.02 (−0.07, 0.03)	−0.02 (−0.07, 0.02)
50–54	565	0.13 (0.06, 0.19)	0.12 (0.06, 0.18)	0.04 (−0.02, 0.10)	0.03 (−0.03, 0.09)
≥55	204	0.15 (0.04, 0.25)	0.14 (0.04, 0.25)	0.03 (−0.06, 0.12)	0.03 (−0.07, 0.12)
Trend *p*-value		<0.001	<0.001	0.337	0.446
Railway noise exposure					
Continuous per 10 dB L_{den}		0.02 (−0.008, 0.04)	0.01 (−0.01, 0.03)	0.02 (−0.003, 0.04)	0.01 (−0.005, 0.04)
Categorical, dB L_{den}					
<45	4,788	0 Referent	0 Referent	0 Referent	0 Referent
45–49	161	0.02 (−0.09, 0.14)	0.01 (−0.10, 0.13)	0.01 (−0.11, 0.10)	−0.01 (−0.11, 0.09)
50–54	125	0.07 (−0.06, 0.20)	0.07 (−0.06, 0.20)	0.10 (−0.02, 0.21)	0.09 (−0.03, 0.20)
≥55	110	−0.04 (−0.18, 0.10)	−0.05 (−0.19, 0.09)	−0.01 (−0.13, 0.12)	−0.02 (−0.14, 0.11)
Trend *p*-value		0.781	0.967	0.448	0.598
Aircraft noise					
Continuous per 10 dB L_{den}		0.16 (0.14, 0.17)	0.16 (0.14, 0.17)	0.03 (0.01, 0.04)	0.03 (0.01, 0.04)
Categorical, dB L_{den}					
<45	4,261	0 Referent	0 Referent	0 Referent	0 Referent
45–49	126	0.32 (0.19, 0.44)	0.31 (0.18, 0.44)	0.12 (0.00, 0.23)	0.11 (−0.008, 0.22)
50–54	590	0.45 (0.39, 0.51)	0.44 (0.38, 0.50)	0.06 (0.008, 0.12)	0.06 (0.006, 0.12)
≥55	207	0.49 (0.39, 0.59)	0.48 (0.39, 0.58)	0.09 (−0.003, 0.18)	0.09 (−0.005, 0.18)
Trend *p*-value		<0.001	<0.001	0.003	0.004

[a]Time-weighted noise exposure expressed as L_{den} taking into account all addresses where the subject had lived during the follow-up period.
[b]Results of linear regression model adjusted only for sex and age.
[c]Results of linear regression model adjusted for sex, age, dietary habits, alcohol consumption, education level, physical activity, smoking status, psychological distress, job strain, and shift work.

departure = 0.099). No corresponding threshold in the exposure–response curve was suggested for aircraft noise.

There were positive trends in incidence of central obesity in relation to aircraft and road traffic noise exposure, with IRRs of 1.19 (95% CI: 1.14, 1.24) and 1.07 (95% CI: 1.00, 1.14) per 10 dB L_{den}, respectively (Table 3). Aircraft noise was also associated with an increased risk of overweight, showing an IRR of 1.06 (95% CI: 1.01, 1.12) per 10 dB L_{den}. In sex-specific analyses, clear associations between road traffic or railway noise exposure and central obesity were only seen in women, whereas trends were apparent in both sexes for aircraft noise (see Table S2). For overweight, a statistically significant trend was only seen in women in relation to aircraft noise exposure. Just as for waist circumference, there seemed to be an increased IRR for central obesity primarily above 45–50 dB L_{den} in relation to road traffic noise exposure, whereas for aircraft noise the trend appears to extend to even lower levels (Table 3, Figure 2).

We observed an exposure–response relation between the number of transportation noise sources and risk of central obesity (Figure 3). The IRR increased from 1.22 (95% CI: 1.08, 1.39) among those exposed to only one source to 2.26 (95% CI: 1.55, 3.29) among those exposed to all three transportation noise sources (*p*-value for trend <0.001). No corresponding trend was seen for overweight. For waist circumference a positive trend was observed with a change of 0.14 cm/y (95% CI: 0.09, 0.18) among those exposed to only one source and of 0.48 cm/y (95% CI: 0.29, 0.67) among those exposed to all three transportation noise sources (*p*-value for trend <0.001) (see Figure S4). On the other hand, no trend was seen in relation to weight gain.

The association between exposure to road traffic noise and waist circumference increase was modified by age, with a higher waist circumference increase among those younger than 60 y at follow-up (see Table S3). No other characteristics showed an interaction with road traffic noise exposure. In particular, there was no apparent effect modification by sex as was seen for central obesity (see Table S2). The association between road traffic noise and weight gain also appeared stronger in the younger age group. The effect modification for aircraft noise exposure generally showed the same pattern as for road traffic noise (data not shown).

In sensitivity analyses, we first explored how the results for central obesity related to exposure to road traffic noise were affected by different restrictions and adjustments (see Figure S5). For exposures of ≥45 dB L_{den} there was an adjusted IRR per 10 dB L_{den} of 1.22 (95% CI: 1.06, 1.42). The IRR appeared to be little affected by additional adjustment for railway noise, aircraft noise, baseline waist circumference, or contextual confounding (using household mean income in small areas) or following exclusion of those with exposure to railway or aircraft noise ≥45 dB L_{den}, address change during follow-up or diabetes heredity. However, a lower IRR was suggested after adjustment for municipality. Second, we explored how results were affected by additional adjustment for local air pollution from road traffic using NO_x as indicator. No marked influence by adjustment for NO_x was seen on the results for different transportation noise sources using waist circumference and weight as continuous outcomes (see Table S4). However, the results on IRR for central obesity related to road traffic noise were affected by adjustment for NO_x (see Table S5). On the other hand, results for overweight or for aircraft or railway noise were not influenced. NO_x was moderately related to road traffic noise ($r = 0.56$) but not to aircraft or railway noise ($r = -0.02$ and 0.14, respectively), which contributes to explaining the consequences of NO_x adjustment on the associations with obesity markers for different transportation noise sources.

Discussion

This cohort study showed an association between exposure to road traffic noise as well as aircraft noise and waist circumference

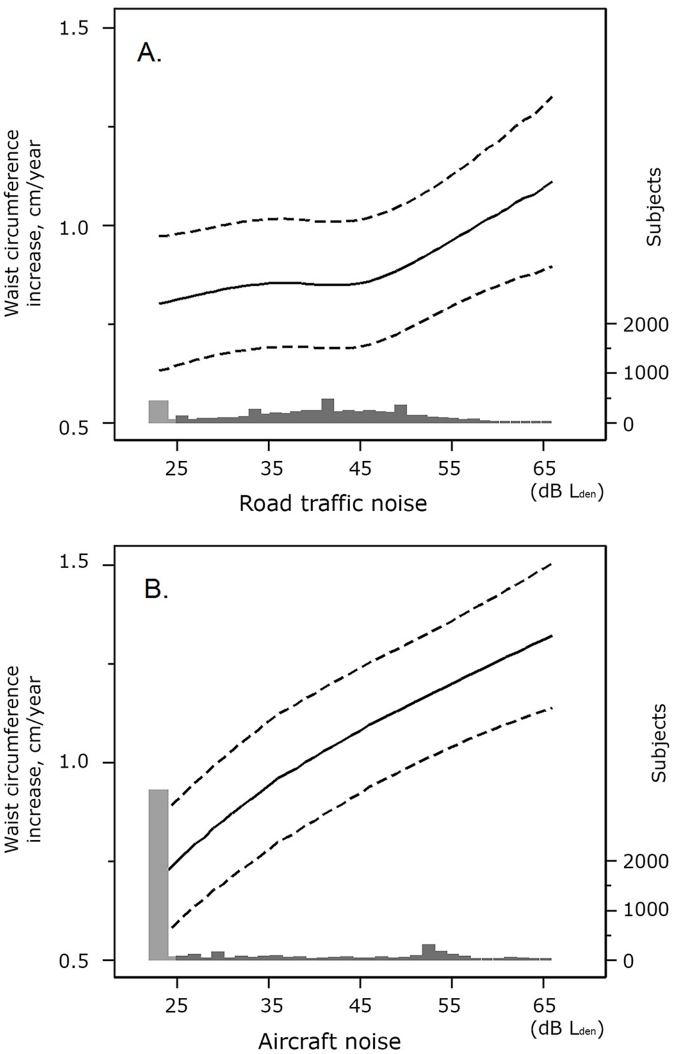

Figure 1. Waist circumference increase (centimeters per year) in the study cohort from Stockholm County in relation to time-weighted exposure to noise from road traffic (*A*) and aircraft (*B*) during follow-up based on restricted cubic spline analyses ($n = 5{,}184$). Note: Increase of waist circumference (bold central line) and 95% CI (dashed outer bands) in models adjusted for sex, age, dietary habits, alcohol consumption, education level, physical activity, smoking status, psychological distress, job strain, and shift work. Bars indicate number of subjects in different exposure groups.

increase. No corresponding association was observed for railway noise. There were positive trends in risk for central obesity related to each of the sources of transportation noise with a particularly high risk in those exposed to all three sources. The excess risk for central obesity primarily occurred at road traffic noise levels of around 50 dB L_{den} and higher, whereas the excess risk related to aircraft noise exposure seemed to occur even at lower levels.

There is growing evidence that transportation noise affects adiposity markers. The first study to investigate this relationship focused on aircraft noise and showed an association particularly for waist circumference (Eriksson et al. 2014). A Norwegian cross-sectional study found a positive association between road traffic noise and BMI only among some subgroups (Oftedal et al. 2015). However, based on a longitudinal study a Danish group reported associations between residential exposure to road traffic or railway noise and waist circumference as well as weight changes in adults (Christensen et al. 2015a), confirming earlier cross-sectional evidence in the same cohort (Christensen et al. 2015b). Our observed waist circumference increase related to road traffic (0.02–0.06 cm/y per 10 dB L_{den}) corresponds well to the findings in the Danish cohort (0.02–0.12 cm/y per 10 dB L_{den}) (Christensen et al. 2015a). A limitation with the Danish study is that the anthropometric data at follow-up were based on self-reports, which are prone to bias. We already published results on transportation noise exposure and obesity markers based on cross-sectional analyses of the same cohort as in present study (Pyko et al. 2015). This new longitudinal analysis used a much more detailed methodology for assessment of noise exposure and showed associations primarily for waist circumference increase in relation to road traffic or aircraft noise exposure as well as for weight gain in relation to aircraft noise exposure. Overall, the evidence is not fully consistent regarding a role for transportation noise in the development of central obesity (increased waist circumference or waist–hip ratio) or general adiposity (weight gain or BMI). Stress mechanisms as mediated by cortisol excretion would be expected to primarily result in central obesity, although noise-induced sleep disturbances and behavioral changes might also mediate effects on general adiposity (Zaharna and Guilleminault 2010). Elucidation of noise effects on specific adiposity markers may provide evidence on causal mechanisms.

In our study, the waist circumference increase per unit of noise exposure was highest for aircraft noise. The effect appeared lower for road traffic noise, and there was no clear association for railway noise. This pattern is well in line with the effect of noise exposure on annoyance and sleep disturbances (Miedema and Oudshoorn 2001; Miedema and Vos 2007) where aircraft noise causes more pronounced effects than road traffic noise at the same noise levels, and railway noise is less harmful than road traffic noise (WHO 2009). Furthermore, our data suggest a threshold in the effects by road traffic noise on waist circumference and central obesity at around 45–50 dB L_{den}, which was not apparent for aircraft noise. Aircraft and road traffic noise are qualitatively different, for example, aircraft noise is transient, more intense in a short period, and usually causes a higher arousal level for areas that are directly under the flight paths, which may contribute to the stronger effects. Furthermore, the exposure assessment approaches to both sources of noise were different in our study. There is a great need for further longitudinal evidence on the association between transportation noise from different sources and obesity.

The risk of central obesity related to road traffic noise exposure $\geq$45 dB L_{den} was mostly unaffected by different adjustments and restrictions. However, the excess risk was no longer statistically significant following adjustment for air pollution from road traffic, using NO_x as marker. On the other hand, no major effect was seen following adjustment for NO_x in analyses of road traffic noise and waist circumference increase. We observed a correlation of 0.56 between exposure to noise and air pollution from road traffic in individuals, which is similar to the correlation in another epidemiological study from Stockholm County (Selander et al. 2009b). Other studies on road traffic noise and obesity have generally not found major changes in associations following adjustment for air pollution (Christensen et al. 2015a, 2015b, 2016; Oftedal et al. 2015). It cannot be excluded that air pollution exposure also contributed to the development of obesity in our study population, although we did not find evidence of any interaction between the two exposures. Furthermore, the association between road traffic noise exposure and central obesity appeared somewhat weaker following adjustment for municipality. However, we did not see any marked effect by adjustment for a large number of individual characteristics or contextual confounding. To generally adjust for municipality is not meaningful in our study because

Table 3. Risks of central obesity and overweight in a cohort from Stockholm County in relation to transportation noise exposure from different sources.

	Central obesity[a]			Overweight[b]		
Exposure	No. of subjects/cases	Model 1[c] IRR (95% CI)	Model 2[d] IRR (95% CI)	No. of subjects/cases	Model 1[c] IRR (95% CI)	Model 2[d] IRR (95% CI)
Road traffic noise[e]						
Continuous per 10 dB L_{den}	4,386/872	1.09 (1.02, 1.16)	1.07 (1.00, 1.14)	2,624/760	1.00 (0.94, 1.07)	0.99 (0.92, 1.05)
Categorical, dB L_{den}						
<45	2,932/548	1.00 Referent	1.00 Referent	1,784/522	1.00 Referent	1.00 Referent
45–49	796/154	1.03 (0.88, 1.21)	1.00 (0.85, 1.17)	461/130	0.97 (0.83, 1.14)	0.96 (0.82, 1.13)
50–54	479/124	1.35 (1.14, 1.60)	1.33 (1.12, 1.58)	276/77	1.02 (0.83, 1.24)	0.99 (0.81, 1.21)
≥55	179/46	1.33 (1.02, 1.72)	1.26 (0.96, 1.64)	103/31	1.06 (0.78, 1.43)	1.04 (0.77, 1.39)
Trend *p*-value		<0.001	0.003		0.837	0.937
Railway noise[e]						
Continuous per 10 dB L_{den}	4,386/872	1.07 (1.00, 1.13)	1.05 (0.99, 1.12)	2,624/760	1.04 (0.97, 1.11)	1.03 (0.96, 1.09)
Categorical, dB L_{den}						
<45	4,057/791	1.00 Referent	1.00 Referent	2,423/702	1.00 Referent	1.00 Referent
45–49	128/25	0.98 (0.69, 1.40)	0.97 (0.68, 1.38)	77/22	1.08 (0.75, 1.54)	1.04 (0.73, 1.49)
50–54	110/33	1.48 (1.10, 1.99)	1.43 (1.07, 1.92)	65/17	0.95 (0.63, 1.44)	0.91 (0.61, 1.36)
≥55	91/23	1.31 (0.92, 1.87)	1.27 (0.88, 1.81)	59/19	1.09 (0.74, 1.59)	1.04 (0.71, 1.52)
Trend *p*-value		0.011	0.025		0.751	0.996
Aircraft traffic noise[e]						
Continuous per 10 dB L_{den}	4,386/872	1.20 (1.15, 1.26)	1.19 (1.14, 1.24)	2,624/760	1.06 (1.01, 1.11)	1.06 (1.01, 1.12)
Categorical, dB L_{den}						
<45	3,590/647	1.00 Referent	1.00 Referent	2,200/620	1.00 Referent	1.00 Referent
45–49	103/22	1.31 (0.90, 1.92)	1.27 (0.87, 1.85)	55/19	1.17 (0.82, 1.67)	1.10 (0.76, 1.58)
50–54	508/145	1.69 (1.45, 1.97)	1.62 (1.39, 1.89)	277/90	1.18 (0.99, 1.41)	1.20 (1.00, 1.44)
≥55	185/58	2.04 (1.64, 2.56)	1.99 (1.58, 2.50)	92/31	1.16 (0.86, 1.56)	1.15 (0.85, 1.55)
Trend *p*-value		<0.001	<0.001		0.047	0.045

[a]Gender-specific cutoff values for central obesity were applied for waist circumference: ≥88 cm for women and ≥102 cm for men. Subjects with central obesity at baseline were excluded from analysis.
[b]Cutoff of BMI at $\geq 25\,kg/m^2$ to define overweight. Subjects with overweight at baseline were excluded from analysis.
[c]Results of Poisson regression model adjusted only for sex and age.
[d]Results of Poisson regression model adjusted for sex, age, dietary habits, alcohol consumption, education level, physical activity, smoking status, psychological distress, job strain, and shift work.
[e]Time-weighted noise exposures expressed as L_{den} taking into account all addresses where the subject had lived during follow-up period.

aircraft noise primarily affected only two municipalities and due to risks of overadjustment for road traffic noise, it would not have made optimal use of the full range of exposure in our study area given the quite low exposures overall. However, we cannot exclude that residual confounding may have affected some of our results.

We saw clear exposure–response associations related to number of noise sources for both risk of central obesity risks and waist circumference increase. This goes in line with previous studies of sleep effects and annoyance in relation to combined exposure to different noise sources (Griefahn et al. 2006; Miedema 2004). Our findings speak in favor of the multiple environmental stressors theory, where several stressors may enhance the effect of each other (Stansfeld and Matheson 2003). Moreover, interactions have been observed between traffic and occupational noise as well as job strain in relation to the risk of myocardial infarction (Selander et al. 2013). Unfortunately, we did not have any data on stress markers for our study subjects, such as saliva cortisol levels. It is important to further investigate interactions between different environmental stressors including noise for both cardiovascular and metabolic outcomes.

We did not observe significant interactions between exposure to road traffic noise and other risk factors in relation to waist circumference increase, except for age. Our results showed that the association between waist circumference increase and road traffic noise were mainly driven by the age group below 60 y. This is congruent with some noise studies on hypertension (Bodin et al. 2009; De Kluizenaar et al. 2007) but opposite to studies focused on stroke and type 2 diabetes, which indicated stronger effects in those over 60 and 64 y of age, respectively (Sørensen et al. 2011, 2013). Moreover, no age interactions were apparent in other noise studies of obesity (Christensen et al. 2015a, 2015b; Oftedal et al. 2015). We did not see an interaction with BMI or waist circumference at baseline. In contrast, Danish longitudinal results showed stronger effects of noise on adiposity development in those obese or with central obesity at baseline (Christensen et al. 2015a). Furthermore, there was no clear effect modification by noise annoyance or sensitivity, which is opposite to Norwegian results with the strongest effect in noise-sensitive women (Oftedal et al. 2015). Although the literature is limited regarding the influence by these factors on the association between noise exposure and obesity, there is evidence of noise annoyance and sensitivity acting as effect modifiers of the relationship between the noise exposure and cardiovascular outcomes (Babisch et al. 2013; Eriksson et al. 2010). All in all, it is not clear if age or other risk factors modify the association between noise and adiposity.

A limitation of our study is the relatively low road traffic noise levels and the small number of highly exposed participants. Furthermore, in certain aspects, the data on noise exposures are imprecise. For example, we lack information on noise exposure other than from the three transportation sources, such as occupational exposure. Additionally, we do not have information on noise modifiers, such as façade and window insulation as well as bedroom location, open/closed windows, use of earplugs, and so forth. Moreover, by design, the study population was enriched with persons with a family history of diabetes and the results may not be generalizable to the population as a whole. However, the associations were confirmed when we restricted the analysis on road traffic and waist circumference to those without a family history of diabetes.

The strengths of the present study include the prospective design and anthropometric data measured by trained nurses at recruitment as well as at follow-up. Additionally, detailed information was available regarding potential individual confounders (socioeconomic position, diet, alcohol consumption, smoking, physical activity, and so forth) as well as area–base confounders.

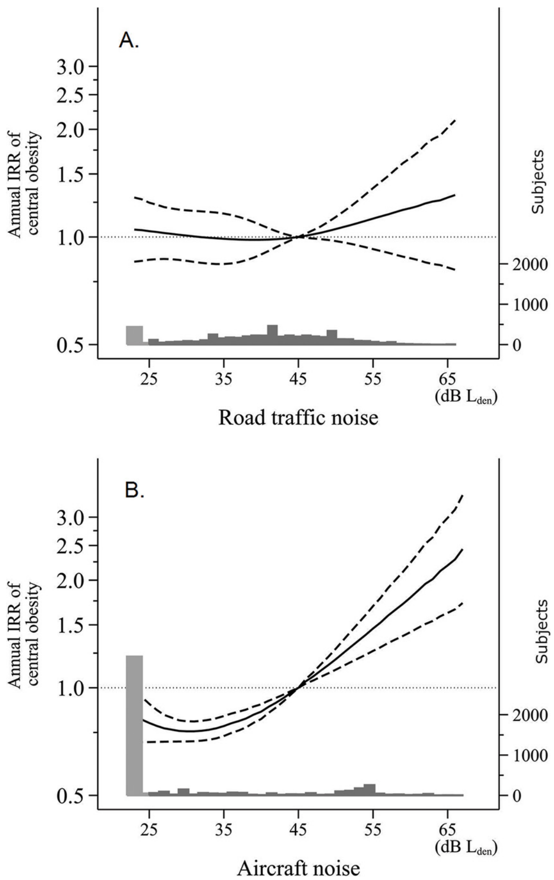

Figure 2. Incidence rate ratio for central obesity in the study cohort from Stockholm County in relation to noise exposure from road traffic (*A*) and aircraft (*B*) in the fully adjusted model based on restricted cubic spline analyses ($n = 4{,}386$). Note: IRR of central obesity (bold central line) and 95% CI (dashed outer bands) in model adjusted for sex, age, dietary habits, alcohol consumption, education level, physical activity, smoking status, psychological distress, job strain, and shift work, using 45 dB L_{den} as reference level. Bars indicate number of subjects in different exposure groups.

Nevertheless, residual confounding cannot be excluded. Furthermore, we had a detailed residential history for all participants, allowing exposure assessment for the whole follow-up period. A particular feature of our study is that a sizable proportion of the study participants was exposed to several noise sources, allowing evaluation of health effect following exposure to multiple noise sources.

In conclusion, our study showed associations between exposure to noise from road traffic or aircraft and development of central obesity. The risk appeared particularly high for aircraft noise and in those with concomitant exposure to different sources of transportation noise. These findings support the evidence linking noise to development of obesity, which is an outcome of great public health significance.

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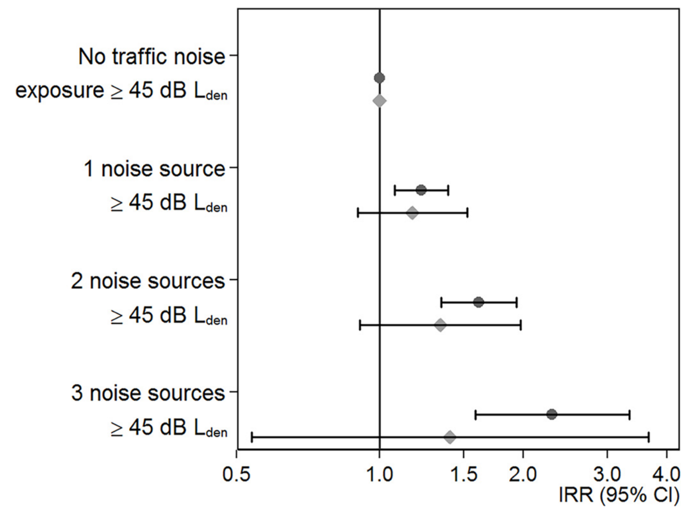

Figure 3. Incidence rate ratio (IRR) of central obesity (●) and overweight (♦) in the study cohort from Stockholm County in relation to noise exposure ≥45 dB L_{den} from road traffic, railways, and/or aircraft. Note: IRRs are adjusted for sex, age, dietary habits, alcohol consumption, education level, physical activity, smoking status, psychological distress, job strain, and shift work.

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