Environment International 187 (2024) 108660

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Full length article

Aircraft noise exposure and body mass index among female participants in two Nurses' Health Study prospective cohorts living around 90 airports in the United States

Matthew Bozigar[a,*], Francine Laden[c,d,e], Jaime E. Hart[c,e], Susan Redline[d,f], Tianyi Huang[c], Eric A. Whitsel[g,h], Elizabeth J. Nelson[i], Stephanie T. Grady[b], Jonathan I. Levy[b], Junenette L. Peters[b]

[a] School of Nutrition and Public Health, College of Health, Oregon State University, 160 SW 26th Street, Corvallis, OR 97331, USA
[b] Department of Environmental Health, Boston University School of Public Health, 715 Albany St., Boston, MA 02118, USA
[c] Channing Division of Network Medicine, Department of Medicine, Brigham and Women's Hospital and Harvard Medical School, 181 Longwood Avenue, Boston, MA 02115, USA
[d] Department of Epidemiology, Harvard T.H. Chan School of Public Health, 677 Huntington Avenue, Boston, MA 02115, USA
[e] Department of Environmental Health, Harvard T.H. Chan School of Public Health, 677 Huntington Avenue, Boston, MA 02115, USA
[f] Department of Medicine, Brigham and Women's Hospital, 221 Longwood Ave, Boston, MA 02215, USA
[g] Department of Epidemiology, Gillings School of Global Public Health, University of North Carolina, Chapel Hill, NC 27599, USA
[h] Department of Medicine, School of Medicine, University of North Carolina, Chapel Hill, NC 27599, USA
[i] College of Arts and Sciences, Boston University, 725 Commonwealth Avenue, Boston, MA 02215, USA

ARTICLE INFO

Handling Editor: Adrian Covaci

Keywords:
Transportation noise
Aircraft noise
Obesity
Body mass index
Cohort study
Body weight

ABSTRACT

Objective: Aircraft noise exposure is linked to cardiovascular disease risk. One understudied candidate pathway is obesity. This study investigates the association between aircraft noise and obesity among female participants in two prospective Nurses' Health Study (NHS and NHSII) cohorts.

Methods: Aircraft day-night average sound levels (DNL) were estimated at participant residential addresses from modeled 1 dB (dB) noise contours above 44 dB for 90 United States (U.S.) airports in 5-year intervals 1995–2010. Biennial surveys (1994–2017) provided information on body mass index (BMI; dichotomized, categorical) and other individual characteristics. Change in BMI from age 18 (BMI18; tertiles) was also calculated. Aircraft noise exposures were dichotomized (45, 55 dB), categorized (<45, 45–54, ≥ 55 dB) or continuous for exposure ≥ 45 dB. Multivariable multinomial logistic regression using generalized estimating equations were adjusted for individual characteristics and neighborhood socioeconomic status, greenness, population density, and environmental noise. Effect modification was assessed by U.S. Census region, climate boundary, airline hub type, hearing loss, and smoking status.

Results: At baseline, the 74,848 female participants averaged 50.1 years old, with 83.0%, 14.8%, and 2.2% exposed to <45, 45–54, and ≥ 55 dB of aircraft noise, respectively. In fully adjusted models, exposure ≥ 55 dB was associated with 11% higher odds (95% confidence interval [95%CI]: −1%, 24%) of BMIs ≥ 30.0, and 15% higher odds (95%CI: 3%, 29%) of membership in the highest tertile of BMI18 (ΔBMI 6.7 to 71.6). Less-pronounced associations were observed for the 2nd tertile of BMI18 (ΔBMI 2.9 to 6.6) and BMI 25.0–29.9 as well as exposures ≥ 45 versus <45 dB. There was evidence of DNL-BMI trends ($p_{\text{trends}} \leq 0.02$). Stronger associations were observed among participants living in the West, arid climate areas, and among former smokers.

Discussion: In two nationwide cohorts of female nurses, higher aircraft noise exposure was associated with higher BMI, adding evidence to an aircraft noise-obesity-disease pathway.

---

* Corresponding author.
E-mail address: matthew.bozigar@oregonstate.edu (M. Bozigar).

https://doi.org/10.1016/j.envint.2024.108660
Received 20 November 2023; Received in revised form 10 April 2024; Accepted 14 April 2024

1. Introduction

Aircraft are a source of transportation noise. Though it has only been partially quantified globally (He et al., 2014), millions of people are exposed to some level of aircraft noise (International Civil Aviation Organization (ICAO), 2023). Aircraft noise has been found to cause higher annoyance than other sources of transportation noise (road, rail) at any noise level (Miedema and Oudshoorn, 2001). Exposure to aircraft noise has been associated with annoyance (Baudin et al., 2020) and many health outcomes (van Kempen et al., 2018), including poor sleep (Bozigar et al., 2023; Nassur et al., 2019b, 2019a), hypertension (Baudin et al., 2020; Kim et al., 2021; Yang et al., 2015), stroke (Weihofen et al., 2019), poor psychological health (Baudin et al., 2018; Hegewald et al., 2020; Seidler et al., 2017), cancer (Hegewald et al., 2017), coronary heart disease, cardiovascular disease, and related mortality (Correia et al., 2013; Evrard et al., 2015; Hansell et al., 2013; Héritier et al., 2017; Roca-Barceló et al., 2021). However, there have also been no associations found with some cardiovascular and mental health outcomes (Grady et al., 2023; Nguyen et al., 2023; Wicki et al., 2023).

Environmental noise has been linked to stress responses, which subsequently influence physiological, metabolic, and immunological functioning (An et al., 2018; Babisch, 2003; Sivakumaran et al., 2022; van Kempen et al., 2018). Dysregulation of the autonomic nervous system and hypothalamic–pituitary–adrenal axis due to sustained stress responses (Pasquali, 2012) has been shown to increase obesity risk (Björntorp and Rosmond, 2000; Bose et al., 2009). Chronic stress is associated with changes in behaviors, such as overeating, physical inactivity, and curtailed sleep, factors that also increase the risk for obesity (Razzoli et al., 2017; Tomiyama, 2019; Torres and Nowson, 2007). In women, aircraft noise has been linked with increases in salivary cortisol (Selander et al., 2009), which is a stress-response biomarker, as well as with poorer sleep (Bozigar et al., 2023; Smith et al., 2022). Additionally, individuals chronically exposed to psychological stress may have elevated stress responses to subsequent perceived stressors (Aschbacher et al., 2013).

Body mass index (BMI) is commonly used as a proxy for obesity, with higher levels shown to be associated with numerous chronic diseases (Larsson and Burgess, 2021; World Cancer Research Fund International, 2022; World Health Organization, 2000). In addition, changes in body weight across the life course have been investigated as an important disease risk factor (Song et al., 2015), particularly the rapid weight gain from young adulthood to the middle and late adulthood periods (Chen et al., 2019). Environmental noise has been associated with markers of general obesity (e.g., BMI) and central obesity (e.g., waist circumference, waist-hip ratio) (An et al., 2018; Christensen et al., 2016, 2015; Cramer et al., 2019; Foraster et al., 2018; Oftedal et al., 2015; Pyko et al., 2017, 2015). Positive associations have been found between aircraft noise exposure and central obesity (Eriksson et al., 2014; Pyko et al., 2017); however, some studies found no associations (Foraster et al., 2018). Other studies have found positive associations between aircraft noise and diabetes (SØrensen et al., 2013), which, like obesity, is impacted by impairment in insulin action (Verma and Hussain, 2017). However, recent systematic reviews have found minimal evidence of associations between noise and measures of adiposity (Sivakumaran et al., 2022; van Kempen et al., 2018), and as far as we know, no study of aircraft noise and obesity involving United States (U.S.) populations have been published, to date.

Therefore, our objective was to estimate the associations between aircraft noise exposure, BMI, and changes in BMI from young adulthood among participants in two U.S.-based prospective cohorts of female nurses living near 90 major U.S. airports. We hypothesized that exposure to aircraft noise would be associated with higher BMI in the NHS cohorts.

2. Materials and methods

2.1. Study population and period

The study population is comprised of participants from two nationwide prospective cohorts, the Nurses' Health Study (NHS) and the Nurses' Health Study II (NHSII), which have been described in detail elsewhere (Bao et al., 2016a; Morabia, 2016). In brief, at inception in 1976, NHS recruited 121,700 female registered nurses ages 30–55 from 11 large states with state death registries (Belanger et al., 1978). Started in 1989, NHSII recruited 116,429 female registered nurses ages 25–42 from 14 states with large numbers of registered nurses. Cohort participants now live in all 50 states. The study participants were followed biennially by mailed questionnaires, with NHS participants responding to surveys in even years and NHSII participants responding in odd years, with response rates of $\geq$90% (Bao et al., 2016b; Morabia, 2016). The study period for NHS was 1994–2016 and for NHSII was 1995–2017, in which outcome metrics of BMI and aircraft noise exposure estimates were available. The protocol for this study was approved by the Institutional Review Board of Brigham and Women's Hospital, Boston, Massachusetts, and consent was implied through the return of the questionnaire.

2.2. Assessment of obesity outcomes

As an indicator of body fat, BMI was calculated from self-reported anthropometrics. Height was collected on the baseline questionnaire for all participants, and weight was self-reported on each biennial questionnaire. BMI is defined as the ratio of a person's weight (kg) to height-squared (m^2) (Keys et al., 1972). Self-reported BMI was found to be a reliable metric of obesity in this study sample (Rimm et al., 1990). Consistent with World Health Organization definitions, we employed categories in which a BMI of <18.5 was "underweight", 18.5–24.9 was "normal", 25.0–29.9 was "overweight", and $\geq$30.0 was "obese" (World Health Organization, 2000). Furthermore, to analyze differences in BMI from early adulthood to middle and late adulthood, we used a validated approach (Troy et al., 1995) in which we subtracted BMI calculated at the current follow-up from BMI calculated at age 18 (BMI18) from participant-recalled height and weight and grouped into tertiles. Age 18 represents the age of emerging adulthood and a critical period of weight gain (Lanoye et al., 2017); weight change since age 18 has been shown to be a risk factor for mortality in the NHS (Baer et al., 2011). BMI and BMI18 were calculated at each 2-year survey cycle (NHS: even years 1994–2016; NHSII: odd years 1995–2017).

2.3. Assessment of aircraft noise exposures

Day-night average sound level (DNL) is a metric intended to capture cumulative exposure to noise from aircraft over a 24-hour period (U.S. FAA (Federal Aviation Administration), 2022a). Annualized aircraft operations were used to quantify aircraft noise for an average day of the year. DNL is calculated in A-weighted decibels (dB), which selectively weights sound in the range of frequencies heard by humans and includes a 10 dB penalty for aircraft noise occurring between 22:00 and 07:00 (i.e., at night), a daily interval in which background noise levels from non-aircraft sources are generally low. DNL is similar to Lden, the metric commonly used for health decision-making in Europe and other parts of the world, except that Lden has different penalties for aircraft noise during the evening and at night (Brink et al., 2018; World Health Organization Regional Office for Europe, 2018). For this study, the U.S. Federal Aviation Administration's (FAA) Aviation Environmental Design Tool (AEDT) (U.S. FAA (Federal Aviation Administration), 2015) was used by the U.S. Department of Transportation's John A. Volpe National Transportation Systems Center (Volpe) to generate noise contours for 90 U.S. airports for every five years from 1995 to 2010 in 1 dB increments above 44 dB using aircraft operations data from the Official

Aviation Guide (OAG) for 1995 and from Enhanced Traffic Management System for 2000, 2005, and 2010. Further details of this method have been previously described elsewhere (Kim et al., 2021; Simon et al., 2022). The 90 airports included in this study were diverse in their characteristics – five (5.6%) were classified as airline primary hubs, 26 (28.9%) as secondary hubs, 16 (17.8%) as focus cities, and 43 (47.8%) as non-hubs/non-focus cities and together represented 87% of U.S. passenger enplanements (Nguyen et al., 2023; Simon et al., 2022). An airline hub is a central airport that airlines use to transfer passengers between flights as part of the "hub-and-spoke" system; primary hubs are the main centers with the most connections, while secondary hubs have fewer flights. Focus cities are key airports for airlines' point-to-point routes offering direct services rather than connections. In contrast, non-hub/non-focus airports are smaller, with limited flights, primarily serving direct, rather than connecting, passenger traffic.

Briefly, spatial estimation of exposures involved point-in-polygon linkage of geocoded residential address coordinates to temporally contemporaneous, airport-specific aircraft noise contours in 1 dB increments within a geographic information system (ArcGIS version 10.8.1, ESRI). Participants were assigned the DNL value corresponding to the contour in which their residence was located. Coordinates located outside aircraft noise contours but within 22.2 mi (35.7 km) of one of the 90 airports were assigned a value of 44 dB, i.e., 1 dB less than the lowest modeled noise contour of 45 dB. A buffer radius of 22.2 mi (35.7 km) represented the maximum empirical distance from an airport for which we had modeled aircraft noise above DNL of 44 A-weighted decibels (dB).

Every two-year survey cycle, each address was matched to the most recent of the aircraft noise contours provided at five-year intervals (1995, 2000, 2005, 2010) occurring in the past when the survey cycle did not coincide with the year for which there was an aircraft noise contour. For example, NHSII participants in 1999 were temporally matched to the year 1995 aircraft noise contours, while participants in 2001 were temporally matched to the year 2000 aircraft noise contours. Patterns in aircraft noise exposures at the 90 study airports over time are described elsewhere (Nguyen et al., 2023). For participants exposed to noise from multiple airports, noise levels were combined (Kim et al., 2021).

Because the FAA often uses DNL thresholds in decision-making in the U.S. (U.S. FAA (Federal Aviation Administration), 2022b), we dichotomized DNL at two cut points: <45 versus ≥45 and <55 versus ≥55 dB. Furthermore, we assessed the aircraft noise-BMI association by categorizing DNL at <45 dB (reference), 45–54 dB, and ≥55 dB. Last, we assessed associations with continuous aircraft noise per 10 dB among the subset of the population exposed to DNL ≥45 dB.

2.4. Covariates and potential confounders

Covariates and potential confounders were identified from the literature or hypothesized based on *a priori* knowledge and outlined in a theoretical directed acyclic graph (DAG; Supplemental Fig. 1) using the web-based tool, Daggity (Textor et al., 2016). Information on covariates was collected in the biennial survey and included: survey year indicators, cohort indicator (NHS/NHSII), age (continuous), age^2 (continuous), race (White, Black, American Indian, Asian, Hawaiian), individual SES metrics of living alone (yes, no) and spouse's education ($<$high school, high school, $>$high school), U.S. Census region (Northeast, Midwest, South, West), parity (nulliparous, 1–2 children, ≥3 children), postmenopausal status (yes, no, missing), hormone therapy (never, current, former, missing), smoking status (never, former, current, missing), alcohol use (none, >0–4, 5–9, 10–14, 15–29, ≥30 g/day, missing), Alternative Healthy Eating Index (AHEI) diet quality score (quintiles and a missing category) (McCullough and Willett, 2006), and physical activity quantified in reported metabolic equivalent of task (MET) (<3, 3–8, 9–17, 18–26, ≥27 h of total energy expenditure per week, missing) (Ainsworth et al., 1993). When metrics were not assessed during a survey cycle (e.g., diet quality), the values of the most recent cycle's assessed metrics were carried forward.

Potential environmental confounders included quintiles of air pollution (concentration of particulate matter of diameter 2.5 μm or smaller, $PM_{2.5}$), greenness, population density, neighborhood socioeconomic status (nSES), and environmental noise. Air pollution levels were estimated annually at the home address using a spatio-temporal prediction model with high predictive accuracy (Yanosky et al., 2014). Greenness was estimated from thenormalized difference vegetation index (NDVI) at 30 m resolution from annual Landsat satellite imagery in Google Earth Engine by matching each participant's current home address to a corresponding aggregated 270 m grid cell for 2000 to 2017. Population density was estimated in people/km^2 at the census tract level using decennial U.S. Census years 2000 and 2010, linearly interpolating between census years if necessary. At the census tract level, nSES was estimated as a summed z-score from many components of socioeconomic status from the U.S. Census (e.g., area-level race, education, income, home value, nativity, unemployment) (Deville et al., 2022). We used a time-invariant metric of environmental noise at 270 m resolution from the National Park Service model estimating combined noise from topographic, climate, hydrologic, and anthropogenic features including roads and military flight operations (Mennitt et al., 2014). Missing values were generally modeled as a missing category.

2.5. Inclusion and exclusion criteria

Participants with at least one successfully geocoded residential address at baseline that was linkable to environmental metrics (e.g., aircraft noise estimates) during our study period were included. Residential addresses were updated every biennial survey to capture participant moves. Participants were excluded at baseline or had their person-time excluded during follow-up if they did not reside within 22.2 mi (35.7 km) of one of 90 study airports. Participants living in areas outside the 22.2 mi (35.7 km) buffers could have lived closer to airports not included in the study, as well as in areas different from those of the population most likely to be exposed to aircraft noise from one of the 90 study airports. Participants were also excluded if they ever developed diabetes or cancer and at any time-period. Participant-years were also excluded if participants died, were currently pregnant, were missing outcome measures, had missing aircraft noise exposure estimates, or were missing other potential spatial confounders (e.g., neighborhood socioeconomic status, nSES, U.S. Census region, greenness, environmental noise, or population density). Finally, the $<2\%$ of the participant-years during which participants were classified as "underweight" (BMI <18.5) (World Health Organization, 2000) were excluded as there were too few participants in this category to facilitate statistical modeling. Supplementary Table 1 shows the counts and percentages of participants excluded by criteria at baseline and throughout the study period.

2.6. Statistical analyses

We used repeated participant measures of BMI and BMI18 linked to exposure data also updated over time. For all statistical analyses, generalized estimating equations (GEE) in SAS 9.4 (SAS Institute) were used to estimate associations among repeated measures as mixed models did not fully converge. We used an independent covariance matrix, the default for the GEE procedure to facilitate convergence, as well. Categories of BMI and BMI18 were modeled using multinomial logistic regression, in which odds ratios were interpreted as odds of membership in a category of BMI ≥25.0 (either 25.0–29.9 or ≥30.0) and BMI18 tertile (second or third) compared to respective reference groups (BMI: 18.5–24.9; BMI18: first tertile) for those exposed to aircraft noise. For continuous DNL, we estimated odds ratios and interpreted them as odds of BMI 25.0–29.9 or ≥30.0 and BMI18 second or third tertile from exposure to a 10 dB increase. In a sensitivity analysis, we modeled continuous BMI as a linear outcome. Linear regression assumptions using a log-standardized version of continuous BMI [ln(BMI)] were empirically assessed while fitting linear regression models. Potential trends between aircraft noise and BMI were estimated by using DNL 10 dB categories as continuous values and assessing the resulting coefficient for this version of DNL.

Our model building strategy consisted of first adjusting for the linear and quadratic effects of age, survey period, and cohort (Model 0). Then, we additionally adjusted for individual factors region of residence, race, living alone, spouse's education, parity, post-menopausal status, hormone therapy, smoking status, alcohol use, diet quality, and physical activity (Model 1). Finally, we added to Model 1 potential environmental confounders when they changed the association between DNL and BMI (Model 2).

Hypothesized effect measure modification by U.S. Census region of residence (Northeast, Midwest, South, West), U.S. climate boundary (humid, arid), airline hub type (non-hub/non-focus city, focus city, hub), self-reported hearing loss (none, any), and smoking status (never, former, current) was assessed. Addresses east of the 100th meridian (west of the prime meridian) were considered humid, while those west

Table 1
Characteristics of female participants in the Nurses' Health Study (NHS) and NHSII at baseline (NHS: 1994; NHSII: 1995) overall and by aircraft day-night average sound level (DNL) exposure group.

	Overall	**Day-night average sound level (DNL) group**					
		Nurses' Health Study			**Nurses' Health Study II**		
		<45 dB	**45–54 dB**	**≥ 55 dB**	**<45 dB**	**45–54 dB**	**≥ 55 dB**
	N = 74,848	N = 30,794	N = 5,193	N = 775	N = 31,352	N = 5,849	N = 885
Demographics							
Age, yr (SD)	50.1 (11.2)	59.7 (7.1)	60.0 (7.1)	60.2 (6.9)	40.8 (4.5)	40.7 (4.5)	40.6 (4.5)
Region of residence							
Northeast, %	43.1	49.5	57.9	59.8	34.7	37.5	49.5
Midwest, %	21.5	15.0	14.7	8.6	28.0	29.9	16.1
South, %	18.6	18.2	16.9	16.8	18.7	21.4	20.7
West, %	16.8	17.3	10.6	14.7	18.6	11.2	13.7
Race							
White, %	95.0	96.4	92.5	89.4	94.8	92.7	87.3
Black, %	2.8	2.2	5.7	9.3	2.3	4.2	6.8
American Indian, %	0.3	0.2	0.3	0.1	0.3	0.3	0.6
Asian, %	1.9	1.2	1.5	1.1	2.4	2.7	5.1
Hawaiian, %	0.1	0.0	0.0	0.0	0.1	0.2	0.1
Currently live alone, %	10.1	9.5	10.5	10.9	10.2	12.7	11.8
Spouse's education							
<High school, %	2.0	3.5	3.9	3.7	0.4	0.7	0.4
High school, %	18.0	24.9	26.1	31.1	11.0	10.9	14.1
>High school, %	55.3	43.2	39.2	32.2	68.3	65.2	63.4
Not married or missing, %	24.7	28.4	30.8	33.0	20.3	23.2	22.1
Parity							
Nulliparous, %	15.9	5.5	5.5	5.3	25.5	28.2	29.2
1–2 children, %	43.4	35.0	35.0	38.5	51.8	49.5	48.6
3 + children, %	39.8	57.6	57.7	54.0	22.7	22.3	22.2
Missing, %	0.9	1.8	1.8	2.3	0.0	0.0	0.0
Post-menopausal							
No, %	51.6	10.8	10.3	12.2	91.1	90.8	92.9
Yes, %	47.2	89.0	89.5	87.8	6.9	6.8	5.5
Missing, %	1.2	0.2	0.2	0.0	2.1	2.4	1.6
HT							
Never, %	60.5	26.1	29.9	31.6	93.1	93.2	94.5
Former, %	22.2	40.3	35.6	31.6	5.5	5.6	4.0
Current, %	8.8	16.6	16.1	17.1	1.3	1.2	1.5
Missing, %	8.5	17.0	18.5	19.7	0.1	0.0	0.0
Smoking status							
Never, %	53.1	42.9	40.7	41.6	63.6	62.1	60.9
Former, %	34.2	43.4	43.9	43.5	25.3	25.4	25.6
Current, %	12.5	13.6	15.1	14.5	11.0	12.3	13.5
Missing, %	0.2	0.2	0.4	0.3	0.1	0.2	0.0
AHEI indicator, %	81.9	83.3	81.3	78.8	81.2	79.9	77.1
Index (SD)	51.3 (10.8)	52.9 (10.6)	52.4 (10.6)	52.7 (10.8)	49.9 (10.7)	49.6 (10.9)	50.3 (10.8)
Alcohol g/day (SD)	4.6 (8.1)	5.5 (9.2)	5.1 (9.1)	4.1 (7.5)	3.9 (6.8)	3.9 (7.3)	3.8 (6.5)
PA indicator, %	94.7	89.6	87.8	86.0	100.0	100.0	100.0
MET hr/week (SD)	20.4 (26.1)	19.9 (24.4)	18.5 (23.0)	17.7 (22.0)	21.0 (27.6)	21.2 (28.4)	21.9 (31.6)
PM2.5, μg/m3 (SD)	14.6 (2.9)	14.5 (2.9)	15.4 (2.9)	15.4 (2.7)	14.4 (3.0)	15.0 (2.8)	14.9 (2.6)
NDVI (SD)	0.33 (0.10)	0.36 (0.10)	0.32 (0.11)	0.28 (0.11)	0.36 (0.10)	0.33 (0.11)	0.29 (0.11)
Pop density, pp/km^2 (SD)	2,250 (4,827)	1,757 (3,296)	3,447 (5,916)	4,452 (6,174)	2,169 (5,215)	3,622 (6,978)	4,221 (5,650)
nSES indicator, %	100.0	100.0	100.0	100.0	100.0	99.9	99.7
Sum z-score (SD)	−0.2 (3.3)	−0.4 (3.3)	−0.5 (3.0)	−0.8 (3.0)	0.0 (3.4)	−0.3 (3.4)	−0.3 (3.1)
EN, dB (SD)	48.5 (2.8)	48.0 (2.7)	49.9 (2.4)	50.7 (2.4)	48.3 (2.9)	50.1 (2.5)	50.5 (2.3)
BMI, kg/m^2 (SD)	26.1 (5.5)	26.3 (5.0)	26.6 (5.2)	26.9 (5.3)	25.8 (5.8)	26.1 (5.9)	26.4 (6.1)
BMI change from age 18, kg/m^2 (SD)	4.8 (4.7)	5.0 (4.5)	5.3 (4.8)	5.4 (4.8)	4.6 (4.7)	4.7 (4.8)	5.0 (4.8)

Values are means (SD) for continuous variables and percentages for categorical variables. Study sample metrics are standardized to the age distribution of the NHS and NHSII cohorts. Values of categorical variables may not sum to 100% due to rounding. dB: decibel, SD: standard deviation, HT: hormone therapy; AHEI: Alternative Healthy Eating Index; PA: physical activity; MET: metabolic equivalent of task; PM$_{2.5}$: concentration of particulate matter 2.5 μm or smaller, NDVI: normalized difference vegetation index; pop: population; nSES: neighborhood socioeconomic status; EN: environmental noise (median daytime); BMI: body mass index.

of the 100th meridian were considered arid (Seager et al., 2018). The few participants living near airports in Hawaii and Alaska were placed in the humid climate category. The two airline hub types of secondary hubs and largest primary hubs were collapsed into a single “hubs” category due to a small count of participants living around the largest primary hubs (Nguyen et al., 2023). In NHS, hearing loss was self-reported in 2006, 2008, 2012, and 2016; in NHSII, hearing loss was self-reported in 2009, 2013, and 2017. Analyses of effect modification by hearing loss were for the period 2006–2017, and values within this period were carried forward if missing. Categories of mild, moderate, or severe hearing loss were grouped and dichotomized as “any” (versus “none”). Interactions between potential effect modifiers and dichotomized aircraft noise exposures were estimated from multinomial models by including respective multiplicative interaction terms and assessed for statistical significance using Type III Wald tests. Additionally, multinomial models of BMI were stratified by the levels of each potential effect modifier to assess the stratum-specific associations between DNL and BMI.

3. Results

3.1. Descriptive results

The 74,848 participants contributed 538,229 observations, averaging 7 observations (median: 8; range: 1–12) per participant throughout the study period. At study baseline, their average age was 50.1 years (standard deviation, SD 11.2), and 83.0%, 14.8%, and 2.2% of the participants were exposed to $<$45, 45–54, and $\geq$55 dB of aircraft noise, respectively (Table 1). Participants primarily lived in the Northeast U.S. (43.1%) (Fig. 1). The study sample of female nurses lacked sociodemographic diversity, with 95.0% identifying as White, 10.1% reporting living alone, and 20.0% having a spouse with a high school education or less.

Key differences were seen across exposure categories among participants by self-identified race, in which a greater proportion of Black participants and correspondingly lower proportions of White participants were exposed to higher levels of aircraft noise. There were large differences across exposure groups for participants’ area population density and environmental noise. Increasing average BMI and BMI18 were evident with increasing categories of aircraft noise exposure.

Characteristics were similar across the cohorts, though some differences were noted. NHS participants were older and lived more in the Northeast than NHSII participants. There were differences related to parity, post-menopausal status, HRT use, smoking status, and alcohol use across the cohorts. Counts of participants excluded by criterion are found in Supplementary Table 1. Three by three cell counts of participants and person-years for DNL and BMI categories overall and within strata of potential effect modifiers are included for reference in Supplementary Tables 2-7.

3.2. Regression results

Environmental factors that altered associations with DNL in multivariable regression models of BMI included greenness, population density, neighborhood socioeconomic status, and environmental noise, and these were included in the fully-adjusted model, Model 2. Of note, air

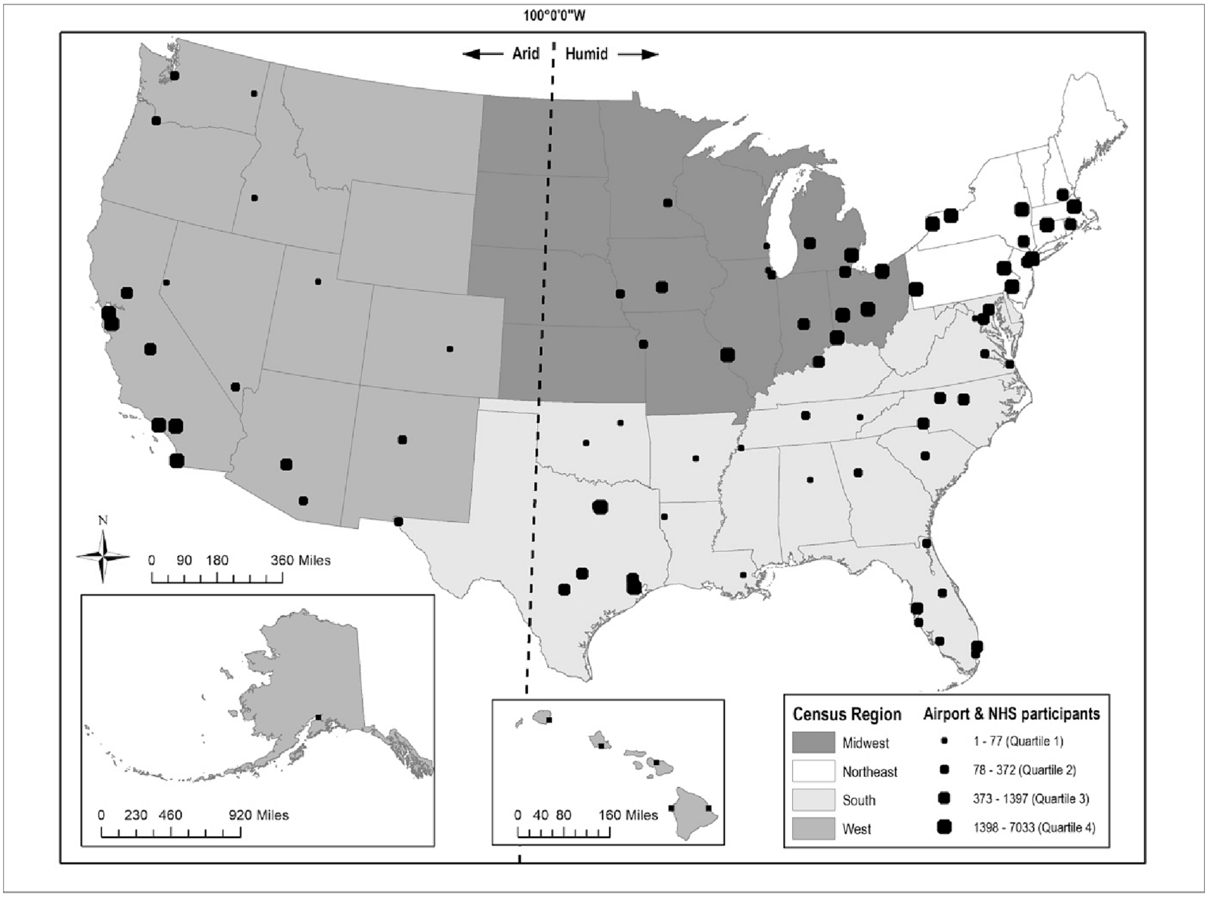

Fig. 1. Locations of 90 study airports in the United States symbolized by quartiles of participants pooled from the Nurses’ Health Study (NHS) and NHSII living around each airport. Increasing point sizes are proportional to the increasing quartiles of study participants from the pooled sample of NHS and NHSII living within 22.2 miles (35.7 km) of each study airport at baseline. States are outlined and colors indicate each of four U.S. Census regions. The 100th meridian west of the Prime Meridian denotes the boundary between arid and humid areas.

pollution was not included in Model 2 as it did not empirically affect the noise-BMI association. Results from Model 2 of categorical BMI indicated 5% higher odds (95%CI: 1%, 9%) of being in the BMI 25.0–29.9 category and 5% higher odds (95%CI: 1%, 10%) of being in the BMI ≥30.0 category versus being in the BMI 18.5–24.9 category among participants exposed to DNL ≥45 dB (Table 2). At the 55 dB cut point, the estimates increased in magnitude to 13% higher odds (95%CI: 3%, 23%) of being in the BMI 25.0–29.9 category and 11% higher odds (95% CI: −1%, 24%) of being in the BMI ≥30.0 category versus being in the BMI 18.5–24.9 category in the fully adjusted model.

For changes in BMI since age 18, associations were modest for the middle tertile (ΔBMI 2.9 to 6.6) relative to the first (ΔBMI −52.3 to 2.8) at either the DNL 45 or 55 dB cut point (Table 2). The estimated associations for the third tertile (ΔBMI 6.7 to 71.6) versus the first tertile were similar in magnitude to the BMI results for the BMI ≥30.0 category versus the BMI 18.5–24.9 category.

We observed 5% higher odds of being in either the BMI 25.0–29.9 category (95%CI: 2%, 8%) or the ≥30.0 category (95%CI: 1%, 9%) from a 10 dB increase in DNL for DNL ≥45 dB (Table 3). Similarly, we saw elevated odds of being in either the 2nd (point estimate: 2%; 95%CI: −1%, 6%) or 3rd (point estimate: 5%; 95%CI: 1%, 9%) tertiles of BMI18 from a 10 dB increase in DNL.

Fig. 2 and Supplementary Table 8 indicate an exposure–response association with a statistically significant trend ($p_{\text{trends}} \leq 0.02$) of higher odds of being in either the BMI 25.0–29.9 category or the BMI ≥30.0 category versus being in the BMI 18.5–24.9 category for increasing exposures to aircraft noise of 45–54 and ≥55 dB versus <45 dB. Adjusting for demographics, lifestyle, and environmental factors attenuated the associations but the exposure–response trends remained.

There were differences in the association between aircraft noise and BMI category by Census region (p = 0.05) (Table 4). For participants living in the West, exposure to DNL ≥45 dB was associated with 14% (95%CI: 3%, 27%) and 26% (95%CI: 10%, 44%) higher odds for participants being in the BMI 25.0–29.9 category or the BMI ≥30.0 category versus being in the BMI 18.5–24.9 category, respectively. Estimated odds ratios nearly doubled when moving the cut point from 45 to 55 dB

Table 3

Results from multinomial logistic regression models of categorical body mass index (BMI) and tertiles of change in BMI from age 18 using a continuous version of day-night average sound level (DNL) exposure for DNL ≥45 dB (dB) by level of adjustment for potential confounding factors in the pooled sample from the Nurses' Health Study (NHS) and NHSII cohorts 1994–2017.

	Odds ratio (95% confidence interval) for DNL 10 dB increase		
	Body mass index categories		
Model	18.5–24.9	25.0–29.9	≥30.0
$N_{\text{observations}}$	251,628	166,916	119,690
$N_{\text{participants}}$	46,202	39,778	24,771
0: Age	Reference	1.09 (1.05, 1.12)	1.14 (1.10, 1.18)
1: 0 + demographics & lifestyle	Reference	1.05 (1.02, 1.08)	1.06 (1.02, 1.10)
2: 1 + environmental	Reference	1.05 (1.02, 1.08)	1.05 (1.01, 1.09)
	Body mass index (kg/m^2) change from age 18		
	Tertile 1	Tertile 2	Tertile 3
	ΔBMI	ΔBMI	ΔBMI
	−52.3–2.8	2.9–6.6	6.7–71.6
$N_{\text{observations}}$	167,523	168,421	167,701
$N_{\text{participants}}$	35,220	41,066	33,444
0: Age	Reference	1.04 (1.01, 1.07)	1.11 (1.07, 1.15)
1: 0 + demographics & lifestyle	Reference	1.02 (0.99, 1.05)	1.04 (1.00, 1.08)
2: 1 + environmental	Reference	1.02 (0.99, 1.06)	1.05 (1.01, 1.09)

Model 0 adjusted for age, age^2, survey period, and cohort. Model 1 adjusted for the covariates in Model 0 as well as region, race, living alone, spouse's education, parity, post-menopausal status, hormone therapy, smoking status, alcohol use, diet quality, and physical activity. Model 2 adjusted for the covariates from Model 1 in addition to greenness, population density, neighborhood socioeconomic status, and environmental noise.

Table 2

Estimated odds ratios (OR) and 95% confidence intervals (CI) for the association between aircraft day-night average sound level (DNL) at thresholds of 45 and 55 dB and categorical body mass index (BMI) and tertiles of change in BMI from age 18 by level of adjustment for potential confounders in the pooled Nurses' Health Study (NHS) and NHSII cohorts 1994–2017.

	Odds ratios (95% confidence interval)					
	Body mass index (kg/m^2) categories					
	DNL ≥45 vs <45 dB			DNL ≥55 vs <55 dB		
Model	18.5–24.9	25.0–29.9	≥30.0	18.5–24.9	25.0–29.9	≥30.0
$N_{\text{observations}}$	251,628	166,916	119,690	251,628	166,916	119,690
$N_{\text{participants}}$	46,202	39,778	24,771	46,202	39,778	24,771
0: Age	Reference	1.09 (1.06, 1.13)	1.16 (1.11, 1.21)	Reference	1.20 (1.09, 1.31)	1.27 (1.14, 1.42)
1: 0 + demographics & lifestyle	Reference	1.05 (1.01, 1.09)	1.07 (1.02, 1.12)	Reference	1.14 (1.04, 1.24)	1.14 (1.02, 1.28)
2: 1 + environmental	Reference	1.05 (1.01, 1.09)	1.05 (1.01, 1.10)	Reference	1.13 (1.03, 1.23)	1.11 (0.99, 1.24)
	Body mass index (kg/m^2) change from age 18					
	Tertile 1	Tertile 2	Tertile 3	Tertile 1	Tertile 2	Tertile 3
	ΔBMI	ΔBMI	ΔBMI	ΔBMI	ΔBMI	ΔBMI
	−52.3 – 2.8	2.9 – 6.6	6.7 – 71.6	−52.3 – 2.8	2.9 – 6.6	6.7 – 71.6
$N_{\text{observations}}$	167,523	168,421	167,701	167,523	168,421	167,701
$N_{\text{participants}}$	35,220	41,066	33,444	35,220	41,066	33,444
0: Age	Reference	1.04 (1.00, 1.08)	1.12 (1.07, 1.17)	Reference	1.09 (0.99, 1.20)	1.26 (1.13, 1.41)
1: 0 + demographics & lifestyle	Reference	1.02 (0.98, 1.06)	1.04 (0.99, 1.09)	Reference	1.07 (0.97, 1.18)	1.15 (1.03, 1.29)
2: 1 + environmental	Reference	1.02 (0.98, 1.06)	1.05 (1.00, 1.10)	Reference	1.07 (0.97, 1.19)	1.15 (1.03, 1.29)

Model 0 adjusted for age, age^2, survey period, and cohort. Model 1 adjusted for the covariates in Model 0 as well as region, race, living alone, spouse's education, parity, post-menopausal status, hormone therapy, smoking status, alcohol use, diet quality, and physical activity. Model 2 adjusted for the covariates from Model 1 in addition to greenness, population density, neighborhood socioeconomic status, and environmental noise.

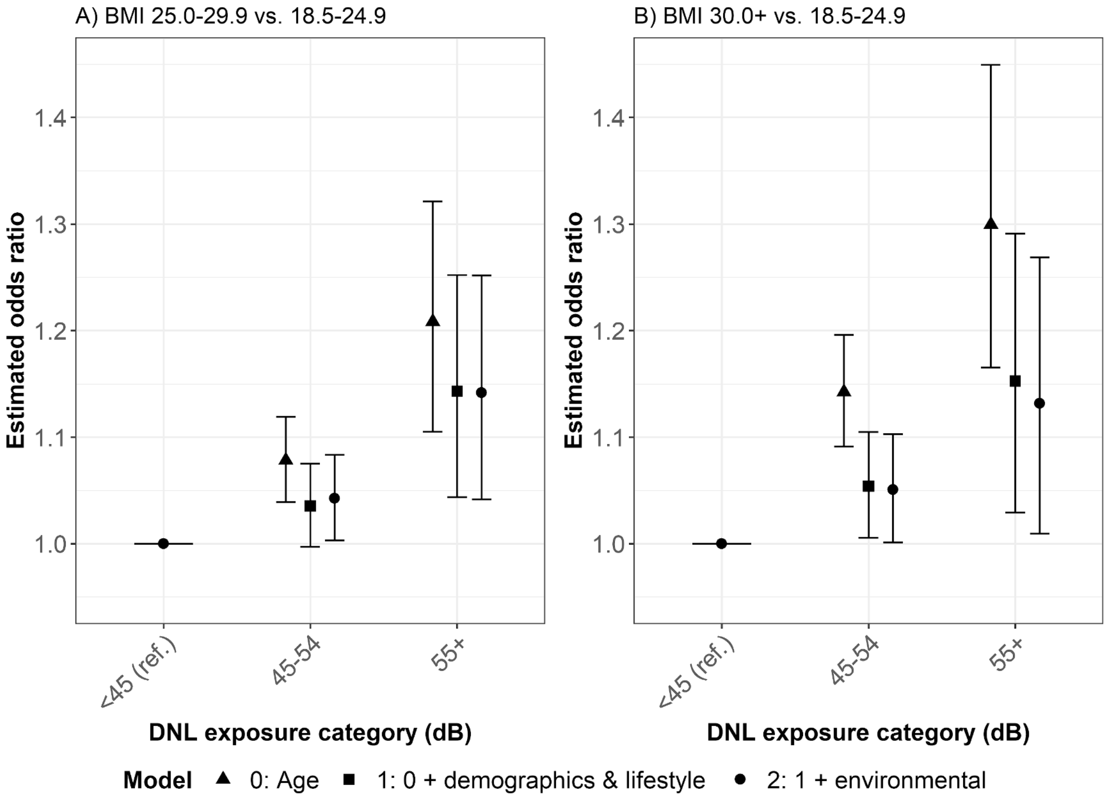

Fig. 2. Estimated odds ratios (OR) and 95% confidence intervals (CI) for the potential exposure–response association between categorical aircraft day-night average sound levels (DNL) in decibels (dB) and categorical body mass index (BMI) by level of adjustment for potential confounding factors in the pooled sample from the Nurses' Health Study (NHS) and NHSII cohorts 1994–2017. * For BMI 25.0–29.9, p_{trend} values were <0.01 for Models 0, 1, and 2. For BMI ≥30.0, p_{trend} values were <0.01 for Models 0 and 1, and p = 0.02 for Model 2. Model 0 adjusted for age, age^2, survey period, and cohort. Model 1 adjusted for the covariates in Model 0 as well as region, race, living alone, spouse's education, parity, post-menopausal status, hormone therapy, smoking status, alcohol use, diet quality, and physical activity. Model 2 adjusted for the covariates from Model 1 in addition to greenness, population density, neighborhood socioeconomic status, and environmental noise.

among participants living in the West region. The largest odds ratios were for participants living in arid climate areas, where differences were found at both the 45 (p = 0.01) and 55 dB (p = 0.05) cut points. For example, the odds of being in the BMI ≥30.0 category versus being in the BMI 18.5–24.9 category for participants living near an airport in an arid region were 52% higher (95%CI: 13%, 104%) for those exposed to DNL ≥55 dB, versus 6% (95%CI: −6%, 19%) for those in a humid region. There was little evidence that the aircraft noise-BMI group association differed by airline hub type, though there was a possible indication of odds ratio decreases from non-hub/non-focus cities to focus cities to hubs for participants exposed to DNL ≥55 dB. Few differences were found by hearing loss status (p = 0.84 at 45 dB; p = 0.27 at 55 dB) or smoking status at the 45 dB cut point (p = 0.99). However, when exposed to DNL ≥55 dB (p = 0.06), participants who were former smokers had 32% higher odds (95%CI: 14%, 53%) of being in the BMI 25.0–29.9 category versus being in the BMI 18.5–24.9 category, although the association attenuated for the BMI ≥30.0 category.

4. Discussion

In this cohort study of females living throughout the U.S., we investigated the association between aircraft noise exposure and an indicator of general obesity, BMI. We had access to data with wide geographic coverage, as exposures were estimated around 90 airports spanning different sizes and covering most of the passenger enplanements across all four Census regions and two main climate types in the U.S. Both BMI outcomes and aircraft noise exposures were available over several decades. We found that aircraft noise exposure at DNL levels ≥45 dB was associated with higher BMI among participants, with the largest associations for exposures ≥55 dB, indicative of an exposure–response relationship. Moreover, exposures to DNL ≥45 dB were also associated with higher BMI of participants since they were 18 years of age.

Evidence of the relationship between exposure to transportation noise and greater obesity to date has been dependent on the study type and objectives, population, and obesity metrics used. All studies of transportation noise and obesity found in the literature to date were conducted in select European populations – Denmark, Switzerland, Oslo, and Stockholm (Christensen et al., 2016, 2015; Cramer et al., 2019; Eriksson et al., 2014; Foraster et al., 2018; Oftedal et al., 2015; Pyko et al., 2017). In a meta-analysis of these seven studies, chronic exposure to transportation noise was associated with higher waist circumference but was not associated with BMI (An et al., 2018).

We found only four studies to date that investigated the associations between aircraft noise and obesity and a fifth that considered aircraft noise as a confounder because there was insufficient statistical power to examine it as a main exposure (Christensen et al., 2016). Three of the studies were located in the greater Stockholm area of Sweden (Eriksson et al., 2014; Pyko et al., 2017, 2015), while the other was located in Switzerland (Foraster et al., 2018). These studies did not find associations between aircraft noise exposure and BMI. As such, these results differed from our central findings of associations between aircraft noise, BMI, and BMI changes since age 18. Why we found associations, but the previous research did not, is poorly understood; however, natural, cultural, physical, and societal differences exist across the U.S. and select European countries previously studied that are hypothesized to play a role. We found no previous studies in the literature that were able to assess changes in obesity from early adulthood to later periods of

Table 4

Estimated odds ratios (OR) and 95% confidence intervals (CI) for potential effect measure modifiers of the association between aircraft day-night average sound level (DNL) and categorical body mass index (BMI) from fully-adjusted models (Model 2) in the pooled Nurses' Health Study (NHS) and NHSII cohorts 1994–2017.

			Odds ratio (95% confidence interval)							
			DNL ≥45 vs <45 dB				DNL ≥55 vs <55 dB			
	$N_{observations}$	$N_{participants}$	BMI 18.5–24.9	BMI 25.0–29.9	BMI ≥30.0	p	BMI 18.5–24.9	BMI 25.0–29.9	BMI ≥30.0	p
Census region	**538,234**	**74,848**				**0.05**				**0.20**
Northeast	226,954	32,652	Reference	1.05 (0.99, 1.12)	1.03 (0.96, 1.11)		Reference	1.09 (0.96, 1.25)	1.05 (0.89, 1.24)	
Midwest	117,909	16,526	Reference	0.98 (0.91, 1.06)	0.96 (0.87, 1.06)		Reference	1.12 (0.91, 1.40)	0.87 (0.66, 1.15)	
South	101,409	15,714	Reference	1.08 (1.00, 1.18)	1.11 (1.00, 1.23)		Reference	1.14 (0.94, 1.38)	1.24 (0.98, 1.57)	
West	91,961	13,374	Reference	1.14 (1.03, 1.27)	1.26 (1.10, 1.44)		Reference	1.23 (0.96, 1.58)	1.46 (1.07, 1.98)	
Climate boundary	**538,234**	**74,848**				**0.01**				**0.05**
Humid	444,764	62,506	Reference	1.04 (1.00, 1.08)	1.04 (0.98, 1.09)		Reference	1.10 (1.00, 1.22)	1.06 (0.94, 1.19)	
Arid	93,470	13,618	Reference	1.14 (1.03, 1.27)	1.26 (1.10, 1.44)		Reference	1.28 (1.00, 1.62)	1.52 (1.13, 2.04)	
Airline hub type	**538,234**	**74,848**				**0.82**				**0.38**
Non-hub/non-focus city	180,061	26,094	Reference	1.07 (1.00, 1.15)	1.03 (0.94, 1.13)		Reference	1.24 (1.02, 1.51)	1.37 (1.07, 1.75)	
Focus city	134,522	19,834	Reference	1.07 (1.00, 1.16)	1.09 (0.99, 1.19)		Reference	1.17 (0.96, 1.41)	1.11 (0.87, 1.41)	
Hubs	223,651	33,531	Reference	1.03 (0.98, 1.09)	1.04 (0.97, 1.12)		Reference	1.09 (0.96, 1.23)	1.04 (0.89, 1.21)	
Hearing loss*	**153,306**	**43,892**				**0.84**				**0.27**
None	104,759	33,149	Reference	1.08 (1.00, 1.17)	1.05 (0.96, 1.15)		Reference	1.37 (1.12, 1.68)	1.11 (0.87, 1.43)	
Any	48,547	17,992	Reference	1.09 (0.98, 1.21)	1.15 (1.01, 1.31)		Reference	1.21 (0.99, 1.64)	1.41 (0.99, 2.03)	
Smoking status	**537,442**	**74,740**				**0.99**				**0.06**
Never	295,576	39,766	Reference	1.05 (1.00, 1.11)	1.07 (1.00, 1.14)		Reference	1.03 (0.90, 1.17)	1.07 (0.92, 1.25)	
Former	197,678	30,845	Reference	1.07 (1.01, 1.14)	1.05 (0.97, 1.13)		Reference	1.32 (1.14, 1.53)	1.18 (0.98, 1.42)	
Current	44,188	11,359	Reference	1.05 (0.95, 1.17)	1.05 (0.92, 1.21)		Reference	1.08 (0.85, 1.39)	1.10 (0.81, 1.50)	

Model 2 adjusted for age, age^2, survey period, cohort (Model 0), region, race, living alone, spouse's education, parity, post-menopausal status, hormone therapy, smoking status, alcohol use, diet quality, physical activity (Model 1), greenness, population density, neighborhood socioeconomic status, and environmental noise. * Analyses of hearing loss did not include all survey years, as it was only available in certain years. In NHS, hearing loss was ascertained in 2006, 2008, 2012, and 2016; in NHSII, hearing loss was ascertained in 2009, 2013, and 2017. "Any" includes mild, moderate, and severe self-reported hearing loss.

adulthood associated with aircraft noise exposure as in this study. More generally, systematic reviews of contemporary studies concluded that there is not enough research and subsequent findings on the subject of noise and BMI to establish a causative link with high certainty (Sivakumaran et al., 2022; van Kempen et al., 2018), indicating the importance of this study and continued research on the subject.

Regarding metrics of central obesity, higher waist circumferences were associated with exposure to aircraft noise over time (Eriksson et al., 2014; Pyko et al., 2017) and cross-sectionally (Pyko et al., 2015) in Stockholm-based studies. In a population-based cohort study in Switzerland, only sources of transportation noise other than aircraft were positively associated (Foraster et al., 2018). In a cohort study in Sweden, excess risk of central obesity was found at levels of aircraft noise below 50 dB, unlike road noise, which indicated significant associations above 50 dB (Pyko et al., 2017). The association with waist circumference was also stronger for aircraft than road noise. Pyko et al. (2017) also found that aircraft noise exposure was linked to weight gain. Our study was unable to assess associations between aircraft noise and indicators of central obesity because such self-reported metrics (e.g., waist circumference) had greater missingness compared to self-reported weight, and the missingness was related to the participant's category of BMI, suggesting the presence of selection bias. Moreover, indicators of central obesity were rarely assessed within the study period (NHS: 1996; NHSII: 1995, 2005).

Our findings in relation to general obesity can be considered alongside prior research in this cohort that indicated that aircraft noise exposure was associated with shorter sleep duration (Bozigar et al., 2023). BMI and sleep are closely intertwined (Larsen et al., 2020), but the directionality of whether higher BMI decreases sleep duration, lower sleep duration increases BMI, neither causes the other because both are downstream effects, or a complex causal interplay between the two is not known. There may be a stronger association between transportation noise and stress metrics for women. The Hypertension and Exposure to Noise near Airports (HYENA) study found that morning salivary cortisol concentrations were significantly higher for women exposed to noise at higher levels (60 dB vs. 50 dB), but greater cortisol concentrations were not observed among men at the same noise levels (Selander et al., 2009).

Though we did not observe large differences by adjusting for other environmental exposures in this study, failing to adjust for them can bias estimates of environmental effects on health (Chaix et al., 2010). One study showed that lower nSES was associated with higher BMI and waist circumference (Leal et al., 2011). Few studies of transportation noise have adjusted for similar area-level confounding factors comprising the built and social environments (Foraster et al., 2018). $PM_{2.5}$ was not observed to be a confounder of the association between aircraft noise and BMI in this study, but previous studies have linked air pollution with increases in BMI in children (Jerrett et al., 2014) and with metabolic syndrome in adults (Eze et al., 2015). Our results provided evidence of confounding of the aircraft noise-BMI association by area greenness, environmental noise, population density, and nSES in the study population given the independent associations each environmental factor had with BMI and correlations with aircraft noise exposure. As these environmental factors are further correlated or even driven by urbanization, which was unmeasured in our study, it is likely that urbanization similarly confounds the association. By excluding participants living greater than 22.2 mi (35.7 km) from a study airport, we helped limit the impact of confounding by urbanization further. Based on our theoretical DAG, the Daggity web tool (Textor et al., 2016) identified a minimally sufficient adjustment set, or the list of the fewest variables (i.e., actual confounders) to condition upon to sufficiently control for bias due to confounding of the association between the exposure and outcome given correct specification of the model, which was comprised of region, physical activity, nSES, environmental noise, and greenness. Main associations found by conditioning on only this set of confounders were qualitatively comparable and slightly larger in quantitative magnitude (possibly from reduced confounding) than those from Model 2 irrespective of the form of the outcome or exposure.

There has been somewhat limited evidence of effect modification of the association between transportation noise and obesity by individual and environmental characteristics. Several studies found no significant interactions (Christensen et al., 2016, 2015; Oftedal et al., 2015), while one study found an interaction between road traffic noise and age with waist circumference increase (Pyko et al., 2017), and another found that obesity was more likely to increase in people with high central obesity at study baseline (Christensen et al., 2015). One study found that the associations between road traffic noise and markers of obesity were stronger among noise-sensitive women (Oftedal et al., 2015). Results from previous research suggested that the association between aircraft noise and sleep was modified by level of hearing loss, with the strongest association in those reporting no hearing loss (Bozigar et al., 2023), though we found limited evidence of effect modification by level of hearing loss in the present study.

In contrast, we found that the association between aircraft noise exposure and BMI was modified by the Census region in which participants lived, the climate region, and to some extent airline hub type and smoking status of the participants. It is possible that aircraft noise is experienced differently in arid regions such as the West – perhaps the finding indicates differences in climate-related factors such as vegetation, temperature, and humidity (Zaporozhets, 2016) and related factors including window opening behaviors (Liu et al., 2021), housing construction and insulation, urbanization, heating/cooling type, time spent outdoors/indoors (Klepeis et al., 2001), etc. Additionally, there are complex, frequency-specific differences in noise levels due to the effects of temperature and humidity (Dreier and Vorländer, 2021) that may not be well-captured by AEDT modeling. Given the strong associations found for arid versus humid regions, further research on geographic and climatic differences on the impact of aircraft noise on obesity is needed. The DNL metric is a summary metric of 24 hr average of aircraft operations of different types (U.S. FAA (Federal Aviation Administration), 2022a), and suggestive evidence of changes in the association with BMI group by airline hub type may be reflective of differential types of aircraft and operations at each airport hub type, which could result in exposure differences not captured by the DNL metric used. Land use compatibility, policies, practices, and development around airport types may further be correlated with residential exposure to aircraft noise (U.S. FAA (Federal Aviation Administration), 2022c), which could manifest as differences in the association by airline hub types. There was evidence of effect modification by smoking status at higher levels of aircraft noise exposure. Smoking can cause endothelial dysfunction and other cardiometabolic issues that may encourage weight loss, and body mass usually increases upon quitting (Tian et al., 2015). However, why the impact of exposure to high levels of aircraft noise may be more strongly associated with BMI among former smokers is largely unknown.

This study was limited by several factors. BMI is a crude metric of general obesity and was self-reported, but self-reports have been shown to be valid in these cohorts (Rimm et al., 1990). Weight at age 18 was participant-recalled and is therefore prone to recall bias. NHS and NHSII assessed height at baseline (NHS: 1976; NHSII: 1989), which was used to calculate BMI along with self-reported weight collected over time (Eckel et al., 2018; Jun et al., 2012). Height changes with age, which could affect the interpretation of BMI (Onwudiwe et al., n.d.; Sorkin et al., 1999). We tightly controlled for linear and quadratic effects of age; however, genetic and lifestyle factors may also affect decline in height (Jelenkovic et al., 2020). Of note, a recent Framingham Heart Study publication demonstrated an advantage of calculating BMI using "young" height over age-related height in assessing chronic disease risk (Holt et al., 2023). The main exposure metric was a 5-year average at residential addresses and was therefore lacking finer spatiotemporal resolution. There may be exposure misclassification, for example, related to time spent at residences versus elsewhere. While there were many "exposed cases" at lower levels of aircraft noise exposure, there were fewer at the highest levels of aircraft noise exposure, such as ≥65 dB, which limited options for analyses of associations at high aircraft noise levels. We were unable to estimate noise at the most exposed façade as is common in recent studies of the health effects of road noise, but this approach is less relevant for studying the health effects of aircraft noise, which originates predominantly from above ground level. Other sources of transportation noise such as roads and railways were not included directly, but we did control for a measure of environmental noise and population density. We were unable to include markers of stress, which prevented investigation of the links between noise, stress, and obesity. In addition, we were unable to include estimates of noise sensitivity or annoyance. We could not include markers of job strain, which has been shown to modify the association between transportation noise and metabolic outcomes (Selander et al., 2013). Moreover, occupational noise exposures were not available for many of the questionnaire cycles. Nonetheless, many of the nurses who were not yet retired were likely exposed similarly due to similarities within the profession and related fields. Finally, there is some possibility of reverse causality, such as people with higher BMIs choosing or being forced into housing nearer airports for socioeconomic or other reasons (Lee, 2020). However, we adjusted for various socioeconomic indicators to mitigate some of these possibilities.

Despite the limitations, this study was strengthened by several factors. This was the first study of aircraft noise exposure and obesity to our knowledge that used a U.S.-based and nation-wide population. This study was able to use repeated measures of aircraft noise exposure, as well as characteristics at individual and neighborhood levels over multiple decades. Most of the main metrics (e.g., BMI, BMI18) used in this study had been previously validated in the NHS cohorts. We were able to investigate changes in BMI from early to late adulthood among the cohort participants. Availability of address-level exposure assignment at relatively low levels of aircraft noise exposure down to 45 dB for the large, national cohorts were additional strengths. The large sample size and repeated measures captured a wide range of participant exposure levels and further enabled us to examine several putative, but uncommonly examined effect measure modifiers at the individual and neighborhood levels.

5. Conclusion

In a population of women living around 90 large airports in the U.S., residential exposure to aircraft noise above 45 dB (DNL) was associated with higher self-reported BMI and recalled change in BMI since age 18 years independent of individual and neighborhood factors. There was a statistically significant trend providing evidence of an increasing aircraft noise exposure-BMI response for DNL ≥45 dB. Associations between aircraft noise exposure and BMI were stronger among participants living in the West, arid climate areas, and who formerly smoked. Aircraft noise and the potential roles of stress and obesity in risk of chronic disease morbidity and mortality deserve further scrutiny.

Funding

This study was funded by Federal Aviation Administration (FAA) 13-C-AJFE-BU-016, under the Aviation Sustainability Center (ASCENT). Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the FAA. Stephanie Grady was supported by the National Institute of Environmental Health Sciences (NIEHS) T32 training grant T32ES014562. Junenette Peters and Jonathan Levy were additionally supported on R01ES025791-01A1, and Jaime Hart and Francine Laden were additionally supported on P30 ES000002. Susan Redline was partially supported by NHLBI R35 HL135818. Eric Whitsel was partly supported by FAA-COE-AJFE-BU-4500004657. We acknowledge the contribution made by the John A. Volpe National Transportation Systems Center in developing the aircraft noise contours. The Nurses' Health Studies are supported by UM1 CA186107, R01 HL150119, R01 HL034594, U01 CA176726, R01 HL35464, and U01 HL145386.

CRediT authorship contribution statement

Matthew Bozigar: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Francine Laden:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Jaime E. Hart:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **Susan Redline:** Writing – review & editing, Methodology, Conceptualization. **Tianyi Huang:** Writing – review & editing, Methodology. **Eric A. Whitsel:** Writing – review & editing. **Elizabeth J. Nelson:** Writing – review & editing, Resources, Conceptualization. **Stephanie T. Grady:** Writing – review & editing, Resources, Methodology. **Jonathan I. Levy:** Writing – review & editing, Methodology, Conceptualization. **Junenette L. Peters:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Susan Redline reports a relationship with Jazz Pharmaceuticals Inc that includes: consulting or advisory and funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgements

We would like to thank the participants and staff of the Nurses' Health Studies, as this study would not be possible without their valuable contributions.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2024.108660.

References

Ainsworth, B.E., Haskell, W.L., Leon, A.S., Jacobs, D.R., Montoye, H.J., Sallis, J.F., Paffenbarger, R.S., 1993. Compendium of Physical Activities: classification of energy costs of human physical activities. Med. Sci. Sports. Exerc 25, 71–80. https://doi.org/10.1249/00005768-199301000-00011.

An, R., Wang, J., Ashrafi, S.A., Yang, Y., Guan, C., 2018. Chronic noise exposure and adiposity: a systematic review and meta-analysis. Doi: 10.1016/j.amepre.2018.04.040.

Aschbacher, K., O`donovan, A., Wolkowitz, O.M., Dhabhar, F.S., Su, Y., Epel, E., 2013. Good Stress, bad stress and oxidative stress: insights from anticipatory cortisol reactivity. Psychoneuroendocrinology 38, 1698–1708. https://doi.org/10.1016/j.psyneuen.2013.02.004.

Babisch, W., 2003. Stress hormones in the research on cardiovascular effects of noise. Noise. Health 5, 1–11.

Baer, H.J., Glynn, R.J., Hu, F.B., Hankinson, S.E., Willett, W.C., Colditz, G.A., Stampfer, M., Rosner, B., 2011. Risk factors for mortality in the nurses' health study: a competing risks analysis. Am. J. Epidemiol 173, 319–329. https://doi.org/10.1093/AJE/KWQ368.

Bao, Y., Bertoia, M.L., Lenart, E.B., Stampfer, M.J., Willett, W.C., Speizer, F.E., Chavarro, J.E., 2016b. Origin, methods, and evolution of the three nurses' health studies. Am. J. Public. Health 106, 1573–1581. https://doi.org/10.2105/AJPH.2016.303338.

Bao, Y., Bertoia, M.L., Lenart, E.B., Stampfer, M.J., Willett, W.C., Speizer, F.E., Chavarro, J.E., 2016a. Origin, Methods, and Evolution of the Three Nurses' Health Studies 106, 1573–1581. Doi: 10.2105/AJPH.2016.303338.

Baudin, C., Lefèvre, M., Champelovier, P., Lambert, J., Laumon, B., Evrard, A.-S., 2018. Aircraft noise and psychological ill-health: the results of a cross-sectional study in France. Int. J. Environ. Res. Public. Health 15, 1642. https://doi.org/10.3390/ijerph15081642.

Baudin, C., Lefèvre, M., Babisch, W., Cadum, E., Champelovier, P., Dimakopoulou, K., Houthuijs, D., Lambert, J., Laumon, B., Pershagen, G., Stansfeld, S., Velonaki, V., Hansell, A., Evrard, A.-S., 2020. The role of aircraft noise annoyance and noise sensitivity in the association between aircraft noise levels and hypertension risk: Results of a pooled analysis from seven European countries. Environ. Res 191, 110179. https://doi.org/10.1016/j.envres.2020.110179.

Belanger, C.F., Hennekens, C.H., Rosner, B., 1978. The nurses' health study. Am. J. Nurs. 78, 1039–1040.

Björntorp, P., Rosmond, R., 2000. Obesity and cortisol. Nutrition 16, 924–936. https://doi.org/10.1016/S0899-9007(00)00422-6.

Bose, M., Oliván, B., Laferrère, B., 2009. Stress and obesity: the role of the hypothalamic–pituitary–adrenal axis in metabolic disease. Curr. Opin. Endocrinol. Diabetes. Obes 16, 340–346. https://doi.org/10.1097/MED.0b013e32832fa137.

Bozigar, M., Huang, T., Redline, S., Hart, J.E., Grady, S.T., Nguyen, D.D., James, P., Nicholas, B., Levy, J.I., Laden, F., Peters, J.L., 2023. Associations between aircraft noise exposure and self-reported sleep duration and quality in the United States-based prospective nurses' health study cohort. Environ. Health. Perspect 131, 47010. https://doi.org/10.1289/EHP10959.

Brink, M., Schäffer, B., Pieren, R., Wunderli, J.M., 2018. Conversion between noise exposure indicators Leq24h, LDay, LEvening, LNight, Ldn and Lden: Principles and practical guidance. Int. J. Hyg. Environ. Health 221, 54–63. https://doi.org/10.1016/j.ijheh.2017.10.003.

Chaix, B., Leal, C., Evans, D., 2010. Opinion: neighborhood-level confounding in epidemiologic studies: unavoidable challenges. Uncertain. Solut. Source:. Epidemiol. 21, 124–127. https://doi.org/10.1097/EDE.0b013e3181c04e70.

Chen, C., Ye, Y., Zhang, Y., Pan, X.F., Pan, A., 2019. Weight change across adulthood in relation to all cause and cause specific mortality: prospective cohort study. BMJ 367. https://doi.org/10.1136/BMJ.L5584.

Christensen, J.S., Raaschou-Nielsen, O., Tjønneland, A., Nordsborg, R.B., Jensen, S.S., Sørensen, T.I.A., Sørensen, M., 2015. Long-term exposure to residential traffic noise and changes in body weight and waist circumference: a cohort study. Environ. Res 143, 154–161. https://doi.org/10.1016/j.envres.2015.10.007.

Christensen, J.S., Raaschou-Nielsen, O., Tjønneland, A., Overvad, K., Nordsborg, R.B., Ketzel, M., 2016. Road traffic and railway noise exposures and adiposity in adults. Environ. Health. Perspect 124, 329–335.

Correia, A.W., Peters, J.L., Levy, J.I., Melly, S., Dominici, F., 2013. Residential exposure to aircraft noise and hospital admissions for cardiovascular diseases: multi-airport retrospective study. BMJ 347, f5561–f. https://doi.org/10.1136/bmj.f5561.

Cramer, J., Therming Jørgensen, J., Sørensen, M., Backalarz, C., Laursen, J.E., Ketzel, M., Hertel, O., Jensen, S.S., Simonsen, M.K., Bräuner, E.V., Andersen, Z.J., 2019. Road traffic noise and markers of adiposity in the Danish nurse cohort: A cross sectional study. Environ. Res 172, 502–510. https://doi.org/10.1016/j.envres.2019.03.001.

Deville, N. V., Iyer, H.S., Holland, I., Bhupathiraju, S.N., Chai, B., James, P., Kawachi, I., Laden, F., Hart, J.E., 2022. Neighborhood socioeconomic status and mortality in the Nurses' Health Study (NHS) and the Nurses' Health Study II (NHSII). Environ. Epidemiol. (in press).

Dreier, C., Vorländer, M., 2021. Aircraft noise—Auralization-based assessment of weather-dependent effects on loudness and sharpness. J. Acoust. Soc. Am 149, 3565–3575. https://doi.org/10.1121/10.0005040.

Eckel, N., Li, Y., Kuxhaus, O., Stefan, N., Hu, F.B., Schulze, M.B., 2018. Transition from metabolic healthy to unhealthy phenotypes and association with cardiovascular disease risk across BMI categories in 90 257 women (the Nurses' Health Study): 30 year follow-up from a prospective cohort study. Lancet. Diabetes. Endocrinol 6, 714–724. https://doi.org/10.1016/S2213-8587(18)30137-2.

Eriksson, C., Hilding, A., Pyko, A., Bluhm, G., Pershagen, G., Östenson, C.G., 2014. Long-term aircraft noise exposure and body mass index, waist circumference, and type 2 diabetes: a prospective study. Environ. Health. Perspect 122, 687–694. https://doi.org/10.1289/ehp.1307115.

Evrard, A.S., Bouaoun, L., Champelovier, P., Lambert, J., Laumon, B., 2015. Does exposure to aircraft noise increase the mortality from cardiovascular disease in the population living in the vicinity of airports? Results of an ecological study in France. Noise. Health 17, 328. https://doi.org/10.4103/1463-1741.165058.

Eze, I.C., Schaffner, E., Foraster, M., Imboden, M., Von Eckardstein, A., Gerbase, M.W., Rothe, T., Rochat, T., Künzli, N., Schindler, C., Probst-Hensch, N., 2015. Long-term exposure to ambient air pollution and metabolic syndrome in adults. PLoS. One 10. https://doi.org/10.1371/JOURNAL.PONE.0130337.

Foraster, M., Eze, I.C., Vienneau, D., Schaffner, E., Jeong, A., Héritier, H., Rudzik, F., Thiesse, L., Pieren, R., Brink, M., Cajochen, C., Wunderli, J.M., Röösli, M., Probst-Hensch, N., 2018. Long-term exposure to transportation noise and its association with adiposity markers and development of obesity. Environ. Int 121, 879–889. https://doi.org/10.1016/j.envint.2018.09.057.

Grady, S.T., Hart, J.E., Laden, F., Roscoe, C., Nguyen, D.D., Nelson, E.J., Bozigar, M., Vopham, T., Manson, J.A.E., Weuve, J., Adar, S.D., Forman, J.P., Rexrode, K., Levy, J.I., Peters, J.L., 2023. Associations between long-term aircraft noise exposure, cardiovascular disease, and mortality in US cohorts of female nurses. Environ. Epidemiol. 7, E259. https://doi.org/10.1097/EE9.0000000000000259.

Hansell, A.L., Blangiardo, M., Fortunato, L., Floud, S., de Hoogh, K., Fecht, D., Ghosh, R. E., Laszlo, H.E., Pearson, C., Beale, L., Beevers, S., Gulliver, J., Best, N., Richardson, S., Elliott, P., 2013. Aircraft noise and cardiovascular disease near Heathrow airport in London: small area study. BMJ 347, f5432–f. https://doi.org/10.1136/bmj.f5432.

He, Q., Wollersheim, C., Locke, M., Waitz, I., 2014. Estimation of the global impacts of aviation-related noise using an income-based approach. Transp. Policy. (oxf) 34, 85–101. https://doi.org/10.1016/J.TRANPOL.2014.02.020.

Hegewald, J., Schubert, M., Wagner, M., Dröge, P., Prote, U., Swart, E., Möhler, U., Zeeb, H., Seidler, A., 2017. Breast cancer and exposure to aircraft, road, and railway-noise: a case–control study based on health insurance records. Scand. J. Work. Environ. Health 43, 509–518. https://doi.org/10.5271/sjweh.3665.

Hegewald, J., Schubert, M., Freiberg, A., Starke, K.R., Augustin, F., Riedel-Heller, S.G., Zeeb, H., Seidler, A., 2020. Traffic noise and mental health: a systematic review and meta-analysis. Int. J. Environ. Res. Public. Health 17, 1–26. https://doi.org/10.3390/IJERPH17176175.

Héritier, H., Vienneau, D., Foraster, M., Eze, I.C., Schaffner, E., Thiesse, L., Rudzik, F., Habermacher, M., Köpfli, M., Pieren, R., Brink, M., Cajochen, C., Wunderli, J.M., Probst-Hensch, N., Röösli, M., 2017. Transportation noise exposure and cardiovascular mortality: a nationwide cohort study from Switzerland. Eur. J. Epidemiol 32, 307–315. https://doi.org/10.1007/s10654-017-0234-2.

Holt, P.R., Altayar, O., Alpers, D.H., 2023. Height with age affects body mass index (BMI) assessment of chronic disease risk. Nutrients 15, 4694. https://doi.org/10.3390/nu15214694.

International Civil Aviation Organization (ICAO), 2023. Global trends in Aircraft Noise [WWW Document]. URL https://www.icao.int/environmental-protection/Pages/Noise_Trends.aspx (accessed 5.11.23).

Jelenkovic, A., Sund, R., Yokoyama, Y., Latvala, A., Sugawara, M., Tanaka, M., Matsumoto, S., Freitas, D.L., Maia, J.A., Knafo-Noam, A., Mankuta, D., Abramson, L., Ji, F., Ning, F., Pang, Z., Rebato, E., Saudino, K.J., Cutler, T.L., Hopper, J.L., Ullemar, V., Almqvist, C., Magnusson, P.K.E., Cozen, W., Hwang, A.E., Mack, T.M., Nelson, T.L., Whitfield, K.E., Sung, J., Kim, J., Lee, J., Lee, S., Llewellyn, C.H., Fisher, A., Medda, E., Nisticò, L., Toccaceli, V., Baker, L.A., Tuvblad, C., Corley, R.P., Huibregtse, B.M., Derom, C.A., Vlietinck, R.F., Loos, R.J.F., Burt, S.A., Klump, K.L., Silberg, J.L., Maes, H.H., Krueger, R.F., McGue, M., Pahlen, S., Gatz, M., Butler, D.A., Harris, J.R., Brandt, I., Nilsen, T.S., Harden, K.P., Tucker-Drob, E.M., Franz, C.E., Kremen, W.S., Lyons, M.J., Lichtenstein, P., Bartels, M., Beijsterveldt, C.E.M. van, Willemsen, G., Öncel, S.Y., Aliev, F., Jeong, H.U., Hur, Y.M., Turkheimer, E., Boomsma, D.I., Sørensen, T.I.A., Kaprio, J., Silventoinen, K., 2020. Genetic and environmental influences on human height from infancy through adulthood at different levels of parental education. Sci. Rep. 10 https://doi.org/10.1038/s41598-020-64883-8.

Jerrett, M., McConnell, R., Wolch, J., Chang, R., Lam, C., Dunton, G., Gilliland, F., Lurmann, F., Islam, T., Berhane, K., 2014. Traffic-related air pollution and obesity formation in children: a longitudinal, multilevel analysis. Environ. Health 13, 49. https://doi.org/10.1186/1476-069X-13-49.

Jun, H.J., Corliss, H.L., Nichols, L.P., Pazaris, M.J., Spiegelman, D., Austin, S.B., 2012. Adult body mass index trajectories and sexual orientation: the nurses' health study II. Am. J. Prev. Med 42, 348–354. https://doi.org/10.1016/J.AMEPRE.2011.11.011.

Keys, A., Fidanza, F., Karvonen, M.J., Kimura, N., Taylor, H.L., 1972. Indices of relative weight and obesity. J. Chronic. Dis 25, 329–343. https://doi.org/10.1016/0021-9681(72)90027-6.

Kim, C.S., Grady, S.T., Hart, J.E., Laden, F., VoPham, T., Nguyen, D.D., Manson, J.A.E., James, P., Forman, J.P., Rexrode, K.M., Levy, J.I., Peters, J.L., 2021. Long-term aircraft noise exposure and risk of hypertension in the Nurses' Health Studies. Environ. Res 112195. https://doi.org/10.1016/j.envres.2021.112195.

Klepeis, N.E., Nelson, W.C., Ott, W.R., Robinson, J.P., Tsang, A.M., Switzer, P., Behar, J. V., Hern, S.C., Engelmann, W.H., 2001. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. J. Expo. Anal. Environ. Epidemiol 11, 231–252. https://doi.org/10.1038/sj.jea.7500165.

Lanoye, A., Brown, K.L., LaRose, J.G., 2017. The transition into young adulthood: a critical period for weight control. Curr. Diab. Rep 17, 114. https://doi.org/10.1007/s11892-017-0938-4.

Larsen, S.C., Horgan, G., Mikkelsen, M.L.K., Palmeira, A.L., Scott, S., Duarte, C., Santos, I., Encantado, J., Driscoll, R.O., Turicchi, J., Michalowska, J., Stubbs, J., Heitmann, B.L., 2020. Association between objectively measured sleep duration, adiposity and weight loss history. Int. J. Obes 44, 1577–1585. https://doi.org/10.1038/s41366-020-0537-3.

Larsson, S.C., Burgess, S., 2021. Causal role of high body mass index in multiple chronic diseases: a systematic review and meta-analysis of Mendelian randomization studies. BMC. Med 19, 320. https://doi.org/10.1186/s12916-021-02188-x.

Leal, C., Bean, K., Thomas, F., Chaix, B., 2011. Are associations between neighborhood socioeconomic characteristics and body mass index or waist circumference based on model extrapolations? Epidemiology 22, 694–703. https://doi.org/10.1097/EDE.0b013e3182257784.

Lee, M., 2020. Obesity among U.S. rural adults: Assessing selection and causation with prospective cohort data. Health Place 61. Doi: 10.1016/j.healthplace.2019.102260.

Liu, J., Liu, J., Lai, D., Pei, J., Wei, S., 2021. A field investigation of the thermal environment and adaptive thermal behavior in bedrooms in different climate regions in China. Indoor. Air 31, 887–898. https://doi.org/10.1111/ina.12775.

McCullough, M.L., Willett, W.C., 2006. Evaluating adherence to recommended diets in adults: the Alternate Healthy Eating Index. Public. Health. Nutr 9, 152–157. https://doi.org/10.1079/PHN2005938.

Mennitt, D., Sherrill, K., Fristrup, K., 2014. A geospatial model of ambient sound pressure levels in the contiguous United States. J. Acoust. Soc. Am 135, 2746–2764. https://doi.org/10.1121/1.4870481.

Miedema, H.M., Oudshoorn, C.G., 2001. Annoyance from transportation noise: relationships with exposure metrics DNL and DENL and their confidence intervals. Environ. Health. Perspect 109, 409–416. https://doi.org/10.1289/ehp.01109409.

Morabia, A., 2016. 120 000 nurses who shook public health. Am. J. Public. Health 106, 1528–1529. https://doi.org/10.2105/AJPH.2016.303345.

Nassur, A.M., Lefèvre, M., Laumon, B., Léger, D., Evrard, A.S., 2019a. Aircraft noise exposure and subjective sleep quality: the results of the DEBATS Study in France. Behavioral. Sleep. Med. 17, 502–513. https://doi.org/10.1080/15402002.2017.1409224.

Nassur, A.M., Léger, D., Lefèvre, M., Elbaz, M., Mietlicki, F., Nguyen, P., Ribeiro, C., Sineau, M., Laumon, B., Evrard, A.S., 2019b. The impact of aircraft noise exposure on objective parameters of sleep quality: results of the DEBATS study in France. Sleep. Med 54, 70–77. https://doi.org/10.1016/j.sleep.2018.10.013.

Nguyen, Daniel D., Levy, J.I., Kim, C., Lane, K.J., Simon, M.C., Hart, J.E., Whitsel, E.A., VoPham, T., Malwitz, A., Peters, J.L., 2023. Characterizing temporal trends in populations exposed to aircraft noise around U.S. airports: 1995–2015. J Expo Sci Environ Epidemiol. Doi: 10.1038/s41370-023-00575-5.

Nguyen, D.D., Whitsel, E.A., Wellenius, G.A., Levy, J.I., Leibler, J.H., Grady, S.T., Stewart, J.D., Fox, M.P., Collins, J.M., Eliot, M.N., Malwitz, A., Manson, J.E., Peters, J.L., 2023b. Long-term aircraft noise exposure and risk of hypertension in postmenopausal women. Environ. Res 218, 115037. https://doi.org/10.1016/j.envres.2022.115037.

Oftedal, B., Krog, N.H., Pyko, A., Eriksson, C., Graff-Iversen, S., Haugen, M., Schwarze, P., Pershagen, G., Aasvang, G.M., 2015. Road traffic noise and markers of obesity – a population-based study. Environ. Res 138, 144–153. https://doi.org/10.1016/j.envres.2015.01.011.

Onwudiwe, N.C., Stuart, B., Zuckerman, I.H., Sorkin, J.D., n.d. Obesity and Medicare Expenditure: Accounting for Age-Related Height Loss. Doi: 10.1038/oby.2010.145.

Pasquali, R., 2012. The hypothalamic–pituitary–adrenal axis and sex hormones in chronic stress and obesity: pathophysiological and clinical aspects. Ann. N. Y. Acad. Sci 1264, 20–35. https://doi.org/10.1111/j.1749-6632.2012.06569.x.

Pyko, A., Eriksson, C., Oftedal, B., Hilding, A., Östenson, C.G., Krog, N.H., Julin, B., Aasvang, G.M., Pershagen, G., 2015. Exposure to traffic noise and markers of obesity. Occup. Environ. Med 72, 594–601. https://doi.org/10.1136/oemed-2014-102516.

Pyko, A., Eriksson, C., Lind, T., Mitkovskaya, N., Wallas, A., Ögren, M., Östenson, C.G., Pershagen, G., 2017. Long-term exposure to transportation noise in relation to development of obesity—a Cohort Study. Environ. Health. Perspect 125, 117005. https://doi.org/10.1289/EHP1910.

Razzoli, M., Pearson, C., Crow, S., Bartolomucci, A., 2017. Stress, overeating, and obesity: Insights from human studies and preclinical models. Neurosci. Biobehav. Rev 76, 154–162. https://doi.org/10.1016/j.neubiorev.2017.01.026.

Rimm, E.B., Stampfer, M.J., Colditz, G.A., Chute, C.G., Litin, L.B., Willett, W.C., 1990. Validity of self-reported waist and hip circumferences in men and women. Epidemiology 1, 466–473. https://doi.org/10.1097/00001648-199011000-00009.

Roca-Barceló, A., Nardocci, A., de Aguiar, B.S., Ribeiro, A.G., Failla, M.A., Hansell, A.L., Cardoso, M.R., Piel, F.B., 2021. Risk of cardiovascular mortality, stroke and coronary heart mortality associated with aircraft noise around Congonhas airport, São Paulo, Brazil: a small-area study. Environ. Health 20, 59. https://doi.org/10.1186/s12940-021-00746-7.

Seager, R., Lis, N., Feldman, J., Ting, M., Park Williams, A., Nakamura, J., Liu, H., Henderson, N., 2018. Whither the 100th meridian? The once and future physical and human geography of America's arid-humid divide. Part I: The Story So Far. Earth. Interact 22, 1–22. https://doi.org/10.1175/EI-D-17-0011.1.

Seidler, A., Hegewald, J., Seidler, A.L., Schubert, M., Wagner, M., Dröge, P., Haufe, E., Schmitt, J., Swart, E., Zeeb, H., 2017. Association between aircraft, road and railway traffic noise and depression in a large case-control study based on secondary data. Environ. Res 152, 263–271. https://doi.org/10.1016/j.envres.2016.10.017.

Selander, J., Bluhm, G., Theorell, T., Pershagen, G., Babisch, W., Seiffert, I., Houthuijs, D., Breugelmans, O., Vigna-Taglianti, F., Antoniotti, M.C., Velonakis, E., Davou, E., Dudley, M.L., Järup, L., 2009. Saliva cortisol and exposure to aircraft noise in six European countries. Environ. Health. Perspect 117, 1713–1717. https://doi.org/10.1289/ehp.0900933.

Selander, J., Bluhm, G., Nilsson, M., Hallqvist, J., Theorell, T., Willix, P., Pershagen, G., 2013. Joint effects of job strain and road-traffic and occupational noise on myocardial infarction. Scand. J. Work. Environ. Health 39, 195–203. https://doi.org/10.5271/SJWEH.3324.

Simon, M.C., Hart, J.E., Levy, J.I., Vopham, T., Malwitz, A., Nguyen, D., Bozigar, M., Cupples, L.A., James, P., Laden, F., Peters, J.L., 2022. Sociodemographic Patterns of Exposure to Civil Aircraft Noise in the United States. Environ. Health. Perspect 130, 1–10. https://doi.org/10.1289/EHP9307.

Sivakumaran, K., Ritonja, J., Waseem, H., AlShenaiber, L., Morgan, E., Ahmadi, S., Denning, A., Michaud, D., Morgan, R., 2022. Impact of noise exposure on risk of developing stress-related metabolic effects: a systematic review and meta-analysis. Noise. Health 24, 215. https://doi.org/10.4103/nah.nah_21_22.

Smith, M.G., Cordoza, M., Basner, M., 2022. Environmental noise and effects on sleep: an update to the WHO systematic review and meta-analysis. Environ. Health. Perspect 130. https://doi.org/10.1289/EHP10197/SUPPL_FILE/EHP10197.S001.ACCO.PDF.

Song, M., Hu, F.B., Spiegelman, D., Chan, A.T., Wu, K., Ogino, S., Fuchs, C.S., Willett, W.C., Giovannucci, E.L., 2015. Adulthood weight change and risk of colorectal cancer in the Nurses' Health Study and Health Professionals Follow-up Study. Cancer Prev. Res. (Phila) 8, 620. https://doi.org/10.1158/1940-6207.CAPR-15-0061.

SØrensen, M., Andersen, Z.J., Nordsborg, R.B., Becker, T., TjØnneland, A., Overvad, K., Raaschou-Nielsen, O., 2013. Long-term exposure to road traffic noise and incident diabetes: a cohort study. Environ. Health. Perspect. https://doi.org/10.1289/ehp.1205503.

Sorkin, J.D., Muller, D.C., Andres, R., 1999. Longitudinal change in height of men and women: implications for interpretation of the body mass index: the baltimore longitudinal study of aging. Am. J. Epidemiol 150, 969–977. https://doi.org/10.1093/OXFORDJOURNALS.AJE.A010106.

Textor, J., van der Zander, B., Gilthorpe, M.S., Liśkiewicz, M., Ellison, G.T., 2016. Robust causal inference using directed acyclic graphs: the R package 'dagitty'. Int. J. Epidemiol 45, 1887–1894. https://doi.org/10.1093/IJE/DYW341.

Tian, J., Venn, A., Otahal, P., Gall, S., 2015. The association between quitting smoking and weight gain: a systemic review and meta-analysis of prospective cohort studies. Obesity. Rev. 16, 883–901. https://doi.org/10.1111/OBR.12304.

Tomiyama, A.J., 2019. Stress and Obesity. Annu. Rev. Psychol 70, 703–718. https://doi.org/10.1146/annurev-psych-010418.

Torres, S.J., Nowson, C.A., 2007. Relationship between stress, eating behavior, and obesity. Nutrition 23, 887–894. https://doi.org/10.1016/j.nut.2007.08.008.

Troy, L.M., Hunter, D.J., Manson, J.E., Colditz, G.A., Stampfer, M.J., Willett, W.C., 1995. The validity of recalled weight among younger women. Int. J. Obes. Relat. Metab. Disord 19, 570–572.

U.S. FAA (Federal Aviation Administration), 2015. Aviation Environmental Design Tool (AEDT) [WWW Document]. URL https://aedt.faa.gov/.

U.S. FAA (Federal Aviation Administration), 2022a. Fundamentals of Noise and Sound [WWW Document]. URL https://www.faa.gov/regulations_policies/policy_guidance/noise/basics (accessed 11.29.22).

U.S. FAA (Federal Aviation Administration), 2022b. History of Noise [WWW Document]. URL https://www.faa.gov/regulations_policies/policy_guidance/noise/history (accessed 5.16.23).

U.S. FAA (Federal Aviation Administration), 2022c. LAND USE COMPATIBILITY AND AIRPORTS.

van Kempen, E., Casas, M., Pershagen, G., Foraster, M., 2018. WHO Environmental Noise Guidelines for the European Region: A Systematic Review on Environmental Noise and Cardiovascular and Metabolic Effects: A Summary. Int. J. Environ. Res. Public. Health 15, 379. https://doi.org/10.3390/ijerph15020379.

Verma, S., Hussain, M.E., 2017. Obesity and diabetes: an update. Diabetes. Metabol. Syndrome:. Clin. Res. Rev. 11, 73–79. https://doi.org/10.1016/J.DSX.2016.06.017.

Weihofen, V.M., Hegewald, J., Euler, U., Schlattmann, P., Zeeb, H., Seidler, A., 2019. Aircraft noise and the risk of stroke. Dtsch. Arztebl. Int. https://doi.org/10.3238/arztebl.2019.0237.

Wicki, B., Schäffer, B., Wunderli, J.M., Müller, T.J., Pervilhac, C., Röösli, M., Vienneau, D., 2023. Suicide and transportation noise: a prospective cohort study from Switzerland. Environ. Health. Perspect 131. https://doi.org/10.1289/EHP11587/SUPPL_FILE/EHP11587.S001.ACCO.PDF.

World Cancer Research Fund International, 2022. Diet, activity and cancer [WWW Document]. URL https://www.wcrf.org/diet-activity-and-cancer/ (accessed 11.21.22).

World Health Organization Regional Office for Europe, 2018. WHO environmental noise guidelines for the European Region. Copenhagen, Denmark.

World Health Organization, 2000. Technical Report Series - Obesity: Preventing and Managing the Global Epidemic (1999: Geneva, Switzerland). Geneva, Switzerland.

Yang, K., Cui, Q., Huang, D., Song, X., Tian, J., Wang, Q., 2015. Is there an association between aircraft noise exposure and the incidence of hypertension? A meta-analysis of 16784 participants. Noise. Health 17, 93. https://doi.org/10.4103/1463-1741.153400.

Yanosky, J.D., Paciorek, C.J., Laden, F., Hart, J.E., Puett, R.C., Liao, D., Suh, H.H., 2014. Spatio-temporal modeling of particulate air pollution in the conterminous United States using geographic and meteorological predictors. Environ. Health 13, 1–15. https://doi.org/10.1186/1476-069X-13-63.

Zaporozhets, O., 2016. Aircraft Noise Models for Assessment of Noise Around Airports – Improvements and Limitations By Oleksandr Zaporozhets (Environmental Safety Institute of the National Aviation. ICAO Environmental Report 50–55.

Technical Report Documentation Page

1. Report No. j.envint.2024.108660_pub	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle

Aircraft noise exposure and body mass index among female participants in two Nurses’ Health Study prospective cohorts living around 90 airports in the United States

5. Report Date

April 2024

6. Performing Organization Code

7. Author(s)

Bozigar, M., Laden, F., Hart, J.E., Redline, S., Huang, T., Whitsel, E.A., Nelson, E.J., Grady, S.T., Levy, J.I. and Peters, J.L.,

8. Performing Organization Report No.

9. Performing Organization Name and Address

Center of Excellence for: Alternative Jet Fuels and Environment

Boston University School of Public Health, 715 Albany St., Boston, MA 02118, USA

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

13-C-AJFE-BU-16

12. Sponsoring Agency Name and Address

Federal Aviation Administration
Office of Environment and Energy

13. Type of Report and Period Covered

Journal Article

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Objective: Aircraft noise exposure is linked to cardiovascular disease risk. One understudied candidate pathway is obesity. This study investigates the association between aircraft noise and obesity among female participants in two prospective Nurses’ Health Study (NHS and NHSII) cohorts.

Methods: Aircraft day-night average sound levels (DNL) were estimated at participant residential addresses from modeled 1 dB (dB) noise contours above 44 dB for 90 United States (U.S.) airports in 5-year intervals 1995–2010. Biennial surveys (1994–2017) provided information on body mass index (BMI; dichotomized, categorical) and other individual characteristics. Change in BMI from age 18 (BMI18; tertiles) was also calculated. Aircraft noise exposures were dichotomized (45, 55 dB), categorized (<45, 45–54, ≥55 dB) or continuous for exposure ≥45 dB. Multivariable multinomial logistic regression using generalized estimating equations were adjusted for individual characteristics and neighborhood socioeconomic status, greenness, population density, and environmental noise. Effect modification was assessed by U.S. Census region, climate boundary, airline hub type, hearing loss, and smoking status.

Results: At baseline, the 74,848 female participants averaged 50.1 years old, with 83.0%, 14.8%, and 2.2% exposed to <45, 45–54, and ≥55 dB of aircraft noise, respectively. In fully adjusted models, exposure ≥55 dB was associated with 11% higher odds (95% confidence interval [95%CI]: -1%, 24%) of BMIs ≥30.0, and 15% higher odds (95%CI: 3%, 29%) of membership in the highest tertile of BMI18 (ΔBMI 6.7 to 71.6). Less-pronounced associations were observed for the 2nd tertile of BMI18 (ΔBMI 2.9 to 6.6) and BMI 25.0–29.9 as well as exposures ≥45 versus <45 dB. There was evidence of DNL-BMI trends (ptrends ≤ 0.02). Stronger associations were observed among participants living in the West, arid climate areas, and among former smokers.

Discussion: In two nationwide cohorts of female nurses, higher aircraft noise exposure was associated with higher BMI, adding evidence to an aircraft noise-obesity-disease pathway.

17. Key Words

Transportation noise, Aircraft noise, Obesity, Body mass index, Cohort study, Body weight, ASCENT

18. Distribution Statement

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized