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Ambient Air Pollution Associated with Body Fat Percentages at Different Body Compartments: A Cohort Study of UK Biobank Participants

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Introduction

A few population-based studies have examined the potential obesogenic effects of ambient air pollution.[1–3] However, the measurements of obesity in these studies were restricted to whole-body assessments, including weight, body mass index (BMI), and body fat percentage. With the advancement of bioelectrical impedance technologies, more comprehensive and finessed measurements of adiposity at different body compartments are available. Characterizing the relationship between ambient air pollution and adiposity at different body compartments can deepen the understanding of the association between ambient air pollution and obesity. In this study, we examined the association between ambient air pollution and body fat percentages at different compartments (arm, leg, and trunk) among baseline and cohort participants from the UK Biobank.

Methods

The UK Biobank is a large cohort of approximately half a million participants in the United Kingdom (UK).[4] The baseline survey was conducted between 2006 and 2010. Three rounds of follow-up had been conducted as of January 2021. The assessment at baseline recruitment involved 502,461 participants, whereas the later three rounds included many fewer participants, with 60,922 participants having at least two measurements on body fat percentages.

Annual concentrations of air pollution in 2010 [particulate matter (PM) with aerodynamic diameter $\leq 2.5\ \mu m$ ($PM_{2.5}$), PM coarse (PM_c), PM_{10}, nitrogen dioxide (NO_2), and nitrogen oxides (NO_x)] were estimated at the residential address of each participant using land use regression models, which yielded median model explained variances (R^2) of 71% for $PM_{2.5}$, 68% for PM_c, 77% for PM_{10}, 82% for NO_2, and 78% for NO_x.[5] Cohort longitudinal data analyses were restricted to those who did not move after 2010 to keep the accuracy of exposure measurement. Body fat percentage at different compartments (left arm, right arm, left leg, right leg, and trunk) were measured using the Tanita BC418MA Body Composition Analyzer and bioelectrical impedance analysis at baseline and follow-up visits.

Covariates were selected based on availability of variables and potential confounders that may affect both the exposure and outcome. Age at baseline recruitment was included as a continuous variable. Sex was self-reported as female or male at baseline. Because the UK Biobank includes White participants (>90%), self-reported ethnicity was categorized into a binary variable (White and Other) to avoid convergence issues of regression models. Average total household income before tax was collected at baseline and included six categories: <18,000 £, 18,000–30,999 £, 31,000–51,999 £, 52,000–100,000 £, >100,000 £, and unknown. Smoking status was collected at baseline as a touchscreen question and categorized into never, previous, and current smoker. Rurality was ascertained from the population density of the participant's home postcode and classified as rural or urban. The Townsend deprivation index (TDI) incorporates four aspects, including unemployment, car ownership, home ownership, and household overcrowding. TDI at recruitment was included as continuous variable, and a larger value indicated greater material deprivation. In the longitudinal analysis, time since baseline was further included to account for the effect of time on body fat percentage changes.

For the cross-sectional data, we constructed linear models (lm function in Base R; version 4.1.3) to estimate the association of interquartile range (IQR) increase in air pollutant with the fat percentage at five different compartments. For the cohort longitudinal data, we fitted linear mixed-effects models (lmer function in R package lme4; version 1.1-29) to investigate the association between ambient air pollution and changes in the outcome variables over time.[6] The analytical equation of the linear mixed-effects models is:

$$y_{ij} = \beta_0 + \beta_{1i}\text{year}_{ij} + \beta_2 air_i \times \text{year}_{ij} + \beta_h \text{covariate}_i + \mu_{0i} + \mu_{1i}\text{year}_{ij} + \varepsilon_{ij},$$

where y_{ij} is the body fat percentages at different compartments for participant i at jth measurement occasion; year_{ij} is the follow-up year for participant i at jth measurement, and β_{1i} is the slope of the time trend for participant i; β_2 is our parameter of interest that estimates the association between ambient air pollution and changes in y_{ij} per year; and β_h are parameters for the preselected covariates. In addition, μ_{0i} is participant-level random error, μ_{1i} is participant-level random error for follow-up year, and ε_{ij} is measurement or sampling error. All available repeated measurements of body fat percentages were included in the analyses. We reported the associations between per-IQR increment in ambient air pollution and body fat percentages at compartments at mean follow-up time ($\beta_2 \times \text{IQR} \times 8$ y).[1] The estimates can be interpreted as the additional growth of body fat percentages attributable to an IQR increment in air pollution over 8 y.

Observations with missing exposure, covariate, or outcome variables were excluded from the analyses. All coefficients were considered statistically significant if the 95% confidence interval (CI) excluded null.

Results

Characteristics for the baseline cross-sectional and cohort participants are shown in Table 1. The median age of baseline cross-sectional participants ($n = 444{,}068$) was 56.53 y, 54.43% of them were female, and 94.12% were White; the longitudinal cohort participants ($n = 45{,}036$) were slightly younger (mean age 56.13 y), had fewer females (51.58%) and more Whites (97.04%).

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Table 1. Characteristics of baseline cross-sectional participants ($n = 444{,}068$) and cohort participants ($n = 45{,}036$) overall and by quartiles of ambient $PM_{2.5}$ ($\mu g/m^3$) in 2010 in the UK Biobank.

Baseline cross-sectional participants ($n = 444{,}068$)						
Characteristic	Overall ($n = 444{,}068$)	Quartile 1 (8.17, 9.29) ($n = 111{,}473$)	Quartile 2 (9.29, 9.94) ($n = 112{,}333$)	Quartile 3 (9.94, 10.57) ($n = 110{,}355$)	Quartile 4 (10.57, 21.31) ($n = 109{,}907$)	p-Value[a]
Exposure						
$PM_{2.5}$ [$\mu g/m^3$ (mean ± SD)]	9.98 ± 1.06	—	—	—	—	—
PM_c [$\mu g/m^3$ (mean ± SD)]	6.42 ± 0.9	—	—	—	—	—
PM_{10} [$\mu g/m^3$ (mean ± SD)]	16.23 ± 1.9	—	—	—	—	—
NO_2 [$\mu g/m^3$ (mean ± SD)]	26.58 ± 7.62	—	—	—	—	—
NO_x [$\mu g/m^3$ (mean ± SD)]	43.89 ± 15.61	—	—	—	—	—
Outcomes						
Left arm fat [% (mean ± SD)]	30.39 ± 10.26	29.78 ± 9.91	30.37 ± 10.15	30.72 ± 10.37	30.72 ± 10.57	<0.001
Right arm fat [% (mean ± SD)]	29.50 ± 10.16	28.87 ± 9.79	29.48 ± 10.05	29.83 ± 10.28	29.83 ± 10.48	<0.001
Left leg fat [% (mean ± SD)]	31.92 ± 10.65	31.68 ± 10.46	31.95 ± 10.59	32.11 ± 10.70	31.92 ± 10.85	<0.001
Right leg fat [% (mean ± SD)]	32.00 ± 10.70	31.76 ± 10.50	32.03 ± 10.63	32.21 ± 10.75	32.02 ± 10.90	<0.001
Trunk fat [% (mean ± SD)]	31.13 ± 7.99	30.72 ± 7.82	31.19 ± 7.92	31.38 ± 8.03	31.24 ± 8.19	<0.001
Covariates						
Age [y (mean ± SD)]	56.53 ± 8.08	57.21 ± 7.83	56.86 ± 8.04	56.38 ± 8.14	55.65 ± 8.23	<0.001
Sex [n (%)]	—	—	—	—	—	0.027
Female	241,721 (54.43)	60,803 (54.55)	61,354 (54.62)	60,167 (54.52)	59,397 (54.04)	—
Male	202,347 (45.57)	50,670 (45.45)	50,979 (45.38)	50,188 (45.48)	50,510 (45.96)	—
Ethnicity [n (%)]	—	—	—	—	—	<0.001
Other	26,108 (5.88)	2,826 (2.54)	5,472 (4.87)	7,164 (6.49)	10,646 (9.69)	—
White	417,960 (94.12)	108,647 (97.46)	106,861 (95.13)	103,191 (93.51)	99,261 (90.31)	—
Residence area [n (%)]	—	—	—	—	—	<0.001
Urban	376,841 (84.86)	61,874 (55.51)	100,899 (89.82)	106,260 (96.29)	107,808 (98.09)	—
Rural	67,227 (15.14)	49,599 (44.49)	11,434 (10.18)	4,095 (3.71)	2,099 (1.91)	—
Income [n (%)]	—	—	—	—	—	<0.001
<18,000 £	86,233 (19.42)	15,719 (14.10)	20,116 (17.91)	23,233 (21.05)	27,165 (24.72)	—
18,000–30,999 £	97,355 (21.92)	23,375 (20.97)	25,136 (22.38)	24,926 (22.59)	23,918 (21.76)	—
31,000 − 51,999 £	99,317 (22.37)	26,220 (23.52)	26,148 (23.28)	24,602 (22.29)	22,347 (20.33)	—
52,000 − 100,000 £	77,164 (17.38)	23,160 (20.78)	20,217 (18.00)	17,876 (16.20)	15,911 (14.48)	—
>100,000 £	20,408 (4.60)	7,077 (6.35)	4,652 (4.14)	3,813 (3.46)	4,866 (4.43)	—
Unknown	63,591 (14.32)	15,922 (14.28)	16,064 (14.30)	15,905 (14.41)	15,700 (14.28)	—
Smoking status [n (%)]	—	—	—	—	—	<0.001
Never	243,585 (54.85)	64,280 (57.66)	63,033 (56.11)	60,371 (54.71)	55,901 (50.86)	—
Previous	154,688 (34.83)	38,665 (34.69)	39,175 (34.87)	38,247 (34.66)	38,601 (35.12)	—
Current	45,795 (10.31)	8,528 (7.65)	10,125 (9.01)	11,737 (10.64)	15,405 (14.02)	—
TDI (mean ± SD)	−1.37 ± 3.02	−2.75 ± 2.12	–2.06 ± 2.58	−1.26 ± 2.81	0.63 ± 3.35	<0.001

Cohort participants ($n = 45{,}036$)						
Characteristic	Overall ($n = 45{,}036$)	Quartile 1 (8.17, 9.22) ($n = 11{,}264$)	Quartile 2 (9.22, 9.89) ($n = 11{,}293$)	Quartile 3 (9.89, 10.55) ($n = 11{,}297$)	Quartile 4 (10.55, 18.52) ($n = 11{,}182$)	p-Value[a]
Exposure						
$PM_{2.5}$ [$\mu g/m^3$ (mean ± SD)]	9.94 ± 1.04	—	—	—	—	—
PM_c [$\mu g/m^3$ (mean ± SD)]	6.35 ± 0.87	—	—	—	—	—
PM_{10} [$\mu g/m^3$ (mean ± SD)]	16 ± 1.86	—	—	—	—	—
NO_2 [$\mu g/m^3$ (mean ± SD)]	25.87 ± 7.05	—	—	—	—	—
NO_x [$\mu g/m^3$ (mean ± SD)]	42.81 ± 14.38	—	—	—	—	—
Cohort follow-up						
Number of measurements (mean ± SD)	2.21 ± 0.44	2.21 ± 0.44	2.21 ± 0.44	2.22 ± 0.45	2.22 ± 0.45	0.007
Follow-up time [y (mean ± SD)]	8.00 ± 2.58	7.96 ± 2.62	7.86 ± 2.57	7.99 ± 2.56	8.19 ± 2.56	<0.001
Outcome change at follow-ups						
Left arm fat [% (mean ± SD)]	−0.10 ± 4.00	−0.15 ± 3.86	−0.11 ± 3.90	−0.14 ± 4.02	0.00 ± 4.23	0.023
Right arm fat [% (mean ± SD)]	0.11 ± 4.00	0.05 ± 3.87	0.09 ± 3.89	0.08 ± 4.04	0.22 ± 4.17	0.012
Left leg fat [% (mean ± SD)]	1.36 ± 3.04	1.31 ± 2.98	1.32 ± 2.96	1.35 ± 3.03	1.45 ± 3.19	0.002
Right leg fat [% (mean ± SD)]	1.47 ± 3.23	1.41 ± 3.17	1.44 ± 3.15	1.45 ± 3.22	1.55 ± 3.39	0.008
Trunk fat % (mean ± SD)	0.85 ± 4.38	0.81 ± 4.30	0.79 ± 4.28	0.83 ± 4.41	0.96 ± 4.53	0.017
Covariates						
Age [y (mean ± SD)]	56.13 ± 7.53	56.74 ± 7.27	56.54 ± 7.55	55.94 ± 7.56	55.28 ± 7.64	<0.001
Sex [n (%)]	—	—	—	—	—	0.02
Female	23,230 (51.58)	5,746 (51.01)	5,727 (50.71)	5,835 (51.65)	5,922 (52.96)	—
Male	21,806 (48.42)	5,518 (48.99)	5,566 (49.29)	5,462 (48.35)	5,260 (47.04)	—
Ethnicity [n (%)]	—	—	—	—	—	<0.001
Other	1332 (2.96)	192 (1.70)	267 (2.36)	392 (3.47)	481 (4.30)	—
White	43,704 (97.04)	11,072 (98.30)	11,026 (97.64)	10,905 (96.53)	10,701 (95.70)	—
Residence area [n (%)]	—	—	—	—	—	<0.001
Urban	37,601 (83.49)	5,661 (50.26)	9,994 (88.50)	10,898 (96.47)	11,048 (98.80)	—
Rural	7,435 (16.51)	5,603 (49.74)	1,299 (11.50)	399 (3.53)	134 (1.20)	—
Income [n (%)]	—	—	—	—	—	<0.001
<18,000 £	5,566 (12.36)	978 (8.68)	1,243 (11.01)	1,487 (13.16)	1,858 (16.62)	—
18,000–30,999 £	9,923 (22.03)	2,305 (20.46)	2,494 (22.08)	2,568 (22.73)	2,556 (22.86)	—
31,000–51,999 £	12,143 (26.96)	3,034 (26.94)	3,079 (27.26)	3,083 (27.29)	2,947 (26.35)	—
52,000–100,000 £	10,601 (23.54)	3,027 (26.87)	2,731 (24.18)	2,558 (22.64)	2,285 (20.43)	—
>100,000 £	2,678 (5.95)	847 (7.52)	648 (5.74)	565 (5.00)	618 (5.53)	—
Unknown	4,125 (9.16)	1,073 (9.53)	1,098 (9.72)	1,036 (9.17)	918 (8.21)	—
Smoking status [n (%)]	—	—	—	—	—	<0.001
Never	27,092 (60.16)	7,047 (62.56)	6,972 (61.74)	6,806 (60.25)	6,267 (56.05)	—
Previous	15,225 (33.81)	3,715 (32.98)	3,717 (32.91)	3,812 (33.74)	3,981 (35.60)	—
Current	2,719 (6.04)	502 (4.46)	604 (5.35)	679 (6.01)	934 (8.35)	—
TDI (mean ± SD)	−1.99 ± 2.66	−3.06 ± 1.83	−2.66 ± 2.22	−1.97 ± 2.50	−0.25 ± 3.05	<0.001

Note: —, no data; IQR, interquartile range; NO_2, nitrogen dioxide; NO_x, nitrogen oxides; PM, particulate matter; $PM_{2.5}$, PM with aerodynamic diameter ≤2.5 μm; PM_{10}, PM with aerodynamic diameter ≤10 μm; PM_c, PM coarse; SD, standard deviation; TDI, Townsend deprivation index.
[a]p-Values for means and frequency distributions by $PM_{2.5}$ quartiles were tested using analyses of variance and chi-square tests.

Table 2. Associations (beta coefficients and 95% confidence intervals) between interquartile range increment in ambient air pollution (annual average $PM_{2.5}$, PM_c, PM_{10}, NO_2, and NO_x in 2010) and fat percentages at different body compartments in baseline cross-sectional ($n = 444,068$) and longitudinal cohort ($n = 45,036$) UK Biobank participants.

	Air pollutants	$PM_{2.5}$	PM_c	PM_{10}	NO_2	NO_x
Baseline cross-sectional data[a]	IQR ($\mu g/m^3$)	1.28	0.79	1.76	9.83	16.53
	Arm fat [% (left)], beta (95% CI)	0.115 (0.084, 0.147)	0.06 (0.041, 0.08)	0.065 (0.044, 0.087)	−0.041 (−0.077, −0.005)	0.085 (0.058, 0.112)
	Arm fat [% (right)], beta (95% CI)	0.106 (0.074, 0.137)	0.059 (0.04, 0.078)	0.064 (0.042, 0.085)	−0.044 (−0.08, −0.009)	0.08 (0.053, 0.106)
	Leg fat [% (left)], beta (95% CI)	0.005 (−0.017, 0.027)	0.025 (0.012, 0.039)	−0.007 (−0.021, 0.008)	−0.215 (−0.24, −0.19)	−0.03 (−0.048, −0.011)
	Leg fat [% (right)], beta (95% CI)	0.007 (−0.016, 0.03)	0.025 (0.01, 0.039)	−0.01 (−0.026, 0.005)	−0.222 (−0.249, −0.196)	−0.03 (−0.05, −0.011)
	Trunk fat (%), beta (95% CI)	0.048 (0.018, 0.078)	0.03 (0.011, 0.049)	0.024 (0.004, 0.045)	−0.121 (−0.156, −0.087)	0.027 (0.001, 0.053)
Longitudinal cohort data[b]	IQR ($\mu g/m^3$)	1.32	0.69	1.74	9.27	16.52
	Arm fat [% (left)], beta (95% CI)	0.093 (0.051, 0.134)	0.048 (0.022, 0.074)	0.047 (0.016, 0.078)	0.026 (−0.016, 0.069)	0.061 (0.024, 0.098)
	Arm fat [% (right)], beta (95% CI)	0.103 (0.061, 0.144)	0.05 (0.024, 0.076)	0.05 (0.019, 0.081)	0.038 (−0.004, 0.08)	0.067 (0.03, 0.104)
	Leg fat [% (left)], beta (95% CI)	0.051 (0.02, 0.081)	0.036 (0.016, 0.055)	0.032 (0.009, 0.055)	0.011 (−0.02, 0.043)	0.034 (0.007, 0.062)
	Leg fat [% (right)], beta (95% CI)	0.051 (0.019, 0.084)	0.037 (0.016, 0.057)	0.034 (0.01, 0.058)	0.013 (−0.02, 0.046)	0.036 (0.007, 0.066)
	Trunk fat (%), beta (95% CI)	0.08 (0.035, 0.124)	0.034 (0.006, 0.062)	0.02 (−0.013, 0.054)	−0.004 (−0.05, 0.041)	0.044 (0.003, 0.084)

Note: CI, confidence interval; IQR, interquartile range; NO_2, nitrogen dioxide; NO_x, nitrogen oxides; PM, particulate matter; $PM_{2.5}$, PM with aerodynamic diameter ≤ 2.5 µm; PM_{10}, PM with aerodynamic diameter ≤ 10 µm; PM_c, PM coarse.
[a]Models for cross-sectional data controlled for age, sex, ethnicity, household income, smoking status, Townsend deprivation index, and rurality.
[b]Linear mixed models for cohort data additionally controlled for follow-up time and participant-level variations. In cohort data analyses, the associations between per IQR increment in ambient air pollution and body fat percentages were reported at mean follow-up time ($\beta_2 \times IQR \times 8$ y).[1] These estimates can be interpreted as the additional growth of body fat percentages attributable to IQR increment in air pollution over 8 y.

Table 2 presents the associations between ambient air pollution and body fat percentages at arms, legs, and trunk among baseline and cohort participants. Ambient $PM_{2.5}$, PM_c, PM_{10}, and NO_x were significantly associated with increased body fat percentages at arms and trunk at both baseline and follow-up years. The magnitude of associations for $PM_{2.5}$, PM_c, PM_{10}, and NO_x with body fat percentages at arms was stronger than those at legs and trunk. For example, the β coefficients for ambient $PM_{2.5}$ in baseline cross-sectional models (IQR for $PM_{2.5}$: $1.28\, \mu g/m^3$) were 0.115 (95% CI: 0.084, 0.147) for left arm fat percentage, 0.106 (95% CI: 0.074, 0.137) for right arm fat percentage, and 0.048 (95% CI: 0.018, 0.078) for trunk fat percentage; the estimates in mixed-effects models for longitudinal cohort data (IQR for $PM_{2.5}$: $1.32\, \mu g/m^3$) were: 0.093 (95% CI: 0.051, 0.134) for left arm fat percentage, 0.103 (95% CI: 0.061, 0.144) for right arm fat percentage, and 0.08 (95% CI: 0.035, 0.124) for trunk fat percentage. The magnitude of associations with leg fat percentages in longitudinal cohort models was stronger than that in baseline cross-sectional models (Table 2).

In contrast, the associations between ambient NO_2 and body fat percentages were significantly negative in baseline cross-sectional data models or insignificant in cohort data models (Table 2). The β coefficients for ambient NO_2 in baseline cross-sectional models (IQR for NO_2: $9.83\, \mu g/m^3$) were −0.041 (95% CI: −0.077, −0.005) for left arm fat percentage, −0.044 (95% CI: −0.08, −0.009) for right arm fat percentage, −0.215 (95% CI: −0.24, −0.19) for left leg percentage, −0.222 (95% CI: −0.249, −0.196) for right leg percentage, −0.121 (95% CI: −0.156, −0.087) for trunk fat percentage; the estimates in mixed-effect models for cohort data (IQR for NO_2: $9.27\, \mu g/m^3$) were insignificant: 0.026 (95% CI: −0.016, 0.069) for left arm fat percentage, 0.038 (95% CI: −0.004, 0.08) for right arm fat percentage, 0.011 (95% CI: −0.02, 0.043) for left leg percentage, 0.013 (95% CI: −0.02, 0.046) for right leg percentage, and −0.004 (95% CI: −0.05, 0.041) for trunk fat percentage.

Discussion

A previous study reported significant positive associations of air pollution with BMI, overall body fat percentage, and waist to hip ratio using the UK Biobank cohort.[3] Our study deepens this knowledge by further examining the associations with fat percentages at different body compartments, and we found that the associations were stronger at arms and trunk but less evident at legs among baseline and cohort participants in UK Biobank. These findings suggest important yet unrecognized potential health benefits of reducing air pollution on fat distribution at anatomical compartments, as well as the prevention of subsequent cardiometabolic syndrome and deaths.[7]

Although the biological mechanisms behind the associations are not clear, several hypotheses supported by animal studies may explain our findings. Mice-based experiments suggested that $PM_{2.5}$ could induce adipose tissue inflammation, mediate the susceptibility to inflammation, and subsequently trigger redistribution of adipose tissue to viscera.[8,9] This mechanism is partially supported by our results that the association between ambient air pollution and body percentage had larger effect size and was consistently significant at arms, which is on the upper body where air pollution induced inflammation reaction may have the greatest consequences.

A major limitation of this study is a mismatch between the year of exposure measurement and baseline visit: The exposure was measured in the year of 2010, whereas the baseline visit was conducted between 2006 and 2010. This issue is mitigated by the fact that air pollution in the United Kingdom was relatively unchanged between 2006 and 2010.[10] In addition, the participants were primarily White, the concentration of air pollution was low, and the variation was small, which may limit the generalizability to other population or regions.

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