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The joint association of ambient air pollution and different sleep posture with mild obstructive sleep apnea: A study conducted at Taipei Sleep Center

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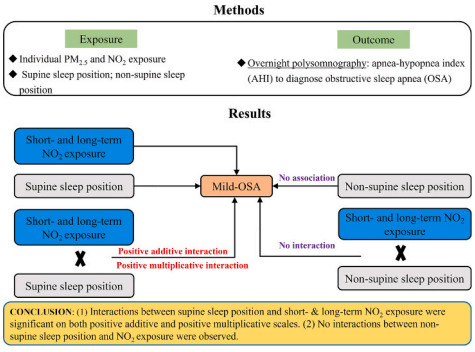
HIGHLIGHTS

- Interaction was adequately evaluated on both additive and multiplicative scales.
- Interaction of different sleep position and air pollution for OSA was described.
- NO_2 but not $PM_{2.5}$ had short- and long-term effects on mild-OSA.
- Supine sleep position exacerbates NO_2-induced OSA.
- Beneficial effects of non-supine position were far less than risks of NO2 exposure.

GRAPHICAL ABSTRACT



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ABSTRACT

Background: Growing evidence suggests the detrimental impact of supine position and air pollution on obstructive sleep apnea (OSA), as well as the potential benefits of nonsupine positions. However, their interaction effects on OSA remain unclear.
Objectives: To evaluate the interaction effects of air pollution (NO_2/$PM_{2.5}$) and sleep position on OSA on additive and multiplicative scales.
Methods: This study included 3330 individuals. Personal exposure to air pollution was assessed using a spatiotemporal model. OSA was diagnosed through polysomnography. The associations of supine and nonsupine positions and air pollutants with mild-OSA and their interaction effects on mild-OSA.

Abbreviations: AHI, apnea–hypopnea index; OSA, obstructive sleep apnea; $PM_{2.5}$, particulate matter with an aerodynamic diameter of ≤2.5 μm; NO_2, nitrogen oxide; IQR, interquartile range; RERI, relative excess risk due to interaction; POSA, positional obstructive sleep apnea; non-POSA, non-positional obstructive sleep apnea.

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were explored through generalized logistic regression.
Results: Supine position and high NO_2 level independently increased the risk of mild-OSA, while $PM_{2.5}$ was not associated with mild-OSA. Significant interactions were observed between supine position and NO_2 at different lag periods (0–7 days, 0–1 year, and 0–2 years) ($P = 0.042$, 0.013, and 0.010, respectively). The relative excess risks due to interactions on the additive scale for 1-week, 1-year, and 2-year NO_2 exposure and supine position were 0.63 (95 % CI: 0.10–1.16), 0.56 (95 % CI: 0.13–0.99), and 0.64 (95 % CI: 0.18–1.10); the corresponding odds ratios for interactions on the multiplicative scale were 1.45 (95 % CI: 1.01–2.07), 1.55 (95 % CI: 1.09–2.22), and 1.60 (95 % CI: 1.12–2.28). The positive interactions persisted in men and participants with obesity. No interaction was observed between nonsupine position and NO_2 levels; nevertheless, significant interactions were noted on both the negative additive and multiplicative scales in men.
Conclusion: Prolonged supine sleep significantly increased the risk of mild-OSA, particularly in men and individuals with obesity. Although the benefits of nonsupine position are considerably less than the risks of NO_2 exposure, avoiding prolonged supine sleep may reduce the risk of mild-OSA caused by high levels of NO_2 in men.

1. Introduction

Obstructive sleep apnea (OSA) is a common form of sleep disorder, which disturbs normal sleep pattern by causing intermittent pauses and restarts in breathing (Park et al., 2011). Repetitive apnea events lead to a decrease in blood oxygen saturation (SpO_2), resulting in hypoxia and hypercapnia (Narkiewicz and Somers, 1997). These physiological changes contribute to increased sympathetic activity, linking sleep apnea to hypertension and other cardiovascular events (Narkiewicz and Somers, 1997).

The Clinical Practice Guideline of the American Academy of Sleep Medicine (AASM) recommends attended laboratory-based polysomnography and a technical home sleep apnea test as the gold standards for OSA diagnosis (Kapur et al., 2017). Polysomnography involves recording various physiological signals, including brain activity, eye movement, muscle activity, and heart rate, to evaluate OSA (Iber and American Academy of Sleep, 2007). Parameters such as respiratory effort, SpO_2 level, and body position are key indicators of breathing function (Iber and American Academy of Sleep, 2007). The apnea-hypopnea index (AHI), which measures the number of obstructive events per hour, is widely used to assess OSA severity. AHI values of $\geq$5, $\geq$15, and $\geq$30 indicate mild, moderate, and severe OSA, respectively (Kapur et al., 2017).

The obstruction of the upper airway due to inadequate motor tone of the tongue or airway dilator muscles during sleep directly increases the predisposition to OSA, which is influenced by age, sex, obesity, and posture (Martin et al., 1997; Mohsenin, 2003; White, 2006). Modifying sleep position from supine to lateral decubitus or prone position may reduce the frequency and severity of obstructive events (Cartwright, 1984; Cartwright et al., 1985; Kavey et al., 1985; Oksenberg et al., 2000). For some patients with less severe OSA, avoiding the supine position could alleviate OSA and improve subjective sleepiness and wakefulness (Kavey et al., 1985). According to AASM criteria and other studies (de Vries et al., 2015; Lee et al., 2017), OSA patients can be classified into positional OSA (POSA) and non-POSA groups based on supine and nonsupine AHI values. The mechanisms by which positional changes improve disordered breathing may include reducing the tendency of the tongue to collapse posteriorly, thereby minimizing the occurrence of pharyngeal obstruction (Neill et al., 1997). Additionally, airway resistance, as determined by airway pressure and respiratory flow, is higher in the supine position, which substantially contributes to OSA (Tvinnereim et al., 1996).

The role of poor lifestyle habits, such as smoking, drinking, and sedentary behavior, in the etiology of OSA is well-documented (Mitra et al., 2021). Furthermore, the negative effects of environmental factors, such as air pollution, on OSA should not be underestimated (Urbanik et al., 2020). The influence of traffic-related air pollutants, specially NO_2 and $PM_{2.5}$, on the severity of OSA has been extensively studied. A Taiwanese study involving patients with sleep disorders found a strong positive association between the annual average levels of $PM_{2.5}$ and NO_2 and AHI values (Shen et al., 2018). However, another Taiwanese study investigated the effects of the daily average levels of $PM_{2.5}$ and NO_2 on AHI values, both for all patients and those with severe OSA, did not find any significant associations (Cheng et al., 2019). A study conducted in the United States reported that exposure to the annual average level of NO_2 substantially increased the adjusted odd ratios for moderate to severe OSA; while no significant effects were observed for $PM_{2.5}$ (Billings et al., 2019). In our previous research, we observed significant effects of both short- and long-term NO_2 exposure on mild-OSA, whereas the effects of $PM_{2.5}$ were nonsignificant (He et al., 2022). It is worth noting that intrapersonal differences, regional variations in air pollution levels, and time-varying vulnerability to OSA may contribute to the inconsistent results observed across studies. Air pollutants can potentially induce OSA by increasing the hyperpermeability of the upper airway through oxidative stress and inflammation or by altering the activity of the sympathetic nervous system (Billings et al., 2019).

To the best of our knowledge, there have been no studies investigating whether the supine sleep position, which is known to potentially increase obstructive respiratory episodes, may exacerbate air pollution–induced OSA. Moreover, there are limited studies focusing on the risk–benefit relationships between nonsupine sleep position, air pollution and the onset of OSA. It is worth noting that the annual average levels of NO_2 and $PM_{2.5}$ in Taiwan have consistently exceeded the guidelines set by the World Health Organization (WHO) (Su et al., 2019). In light of this, our study aimed to examine whether different sleep positions aggravate or mitigate the effects of air pollution on OSA. Both short- and long-term effects of air pollution on OSA were evaluated to provide a comprehensive understanding of the time-varying vulnerability of OSA.

2. Materials and methods

2.1. Ethical considerations

The Joint Institutional Review Board of Taipei Medical University, Taiwan (approval number: N201910048), approved this study. Because there is no direct benefit to the study participants, the requirement for informed consent was waived by the Chinese University of Hong Kong Survey and Behavioral Research Ethics Committee.

2.2. Study participants

This study included participants who were referred to the Sleep Center of Taipei Medical University Hospital for a polysomnography test between January 2015 and September 2021. They were from urban areas in northern Taiwan including Taipei and New Taipei City. The study encompassed adult individuals who sought medical attention at the sleep center due to sleep disorders. However, individuals with comorbidities such as diabetes, cardiopulmonary diseases, cardiovascular disease, bronchiectasis, chronic obstructive pneumonia disease,

venous insufficiency, heart failure, renal failure, and those undergoing dialysis were excluded from the study.

2.3. Personal air pollution exposure

We collected hourly ambient air pollution data, including the levels of $PM_{2.5}$ and NO_2 and daily weather reports for temperature and relative humidity, from 19 air monitoring stations of the Taiwan Environmental Protection Administration (https://data.epa.gov.tw/). In later analysis, we excluded the Yang Ming (No. 64; Taipei), Wan li (No. 3; New Taipei), and Fu Guei Cape (No.84; New Taipei) stations. Because Yang Ming is established in a national park and Wan Li and Fu Guei are established as background stations, they do not monitor the air pollution levels in urban areas. To estimate the levels of exposure to ambient temperature and relative humidity, data from each participant's nearest air monitoring station were used. To estimate the levels of exposure to each pollutant, daily average level data collected from 16 stations were averaged from January 2015 to September 2021. Then, the moving average levels corresponding to lag days 0–1, 0–3, 0–5, 0–7, 0–30, 0–365, and 0–730 were calculated for NO_2 and $PM_{2.5}$. Temporal variations in the NO_2 and $PM_{2.5}$ exposure levels of the participants were evaluated with consideration of the dates of their visit to our sleep center. Spatial variations in the NO_2 and $PM_{2.5}$ exposure levels of the participants were estimated using a validated land use (LUR) regression model (Li et al., 2021). Supervised forward linear regression method was employed to develop LUR models. This modeling approach ensures the inclusion of predictor variables that have a plausible direction of effect, while simultaneously maximizing the predictive accuracy of the established model. Model construction commenced by incorporating the predictor variable with the highest adjusted explained variance (R^2). Subsequently, additional predictor variables were added to the model if they satisfied the following criteria: (1) an increase in adjusted R^2 of no $<$1 %; (2) a pre-defined direction of effect for the predictor variable; (3) variables were included if the probability of F was $<$0.05, and removed if the probability of F was $>$0.10; (4) variables already included in the model maintained the same direction of effect; (5) predictor variables with a variance inflation factor (VIF) exceeding 3 were eliminated to strike a balance between model interpretation and predictive accuracy. The final model allowed for the incorporation of multiple buffer sizes for specific variables (e.g., length of local roads) as long as they adhered to the selection criteria. The established models were evaluated using standard diagnostic tests, as follows. The Cook's distance value was calculated to detect the outliers of data points. Moran's I values on the concentration residuals of the final LUR models were calculated to evaluate the spatial autocorrelation. The performance of the models was assessed by estimating the R^2 and root mean square error (RMSE). To evaluate the predictive capacity of the LUR models, leave-one-out cross-validation (LOOCV) was employed (Li et al., 2021). Furthermore, standard diagnostic tests were descriptively presented, as outlined in Li et al.'s study. In the aforementioned calculation, land use variables, such as population density and vegetation index, were assumed to be associated with air pollution levels and to undergo no substantial changes during the study period.

Finally, the levels of personal exposure were calculated using the following equations: (corresponding estimate of personal exposure evaluated through land use regression in 2019/annual mean air pollution level in 2019) $\times$ the moving average level of each pollutant for lag days 0–1, 0–3, 0–5, 0–7, 0–30, 0–365, and 0–730. This formula that has been introduced in our previous study facilitated the spatiotemporal estimation of air pollution exposure levels, which helped predict the air pollutant levels from personal exposure levels (He et al., 2022).

2.4. Polysomnography

OSA was diagnosed through overnight polysomnography (Embla N7000; Medcare, Iceland) and analyzed using relevant software (Somnologica; Medcare). The AASM criteria were used to score apnea and hypopnea events (Ruehland et al., 2009). Trained and certified sleep technicians performed the entire test, which lasted for $>$6 h. In polysomnography, the following basic sleep-related parameters were directly recorded: total sleep time (min), supine sleep duration, nonsupine sleep duration, sleep efficiency (%), wake after sleep onset (min), mean SpO_2 level, and minimum SpO_2 level. In our current study, we specifically investigated the impact of both supine and nonsupine sleep position. Nonsupine sleep positions encompass sleeping on the right side, left side, and in the prone position (Cerritelli et al., 2022). Peripheral mean SpO_2 level was measured through pulse oximetry (Wong et al., 2021). Composite index AHI values were calculated by dividing all apnea and hypopnea events throughout the night by the total number of sleep hours. Apnea was defined as $\geq$90 % reduction in airflow for $\geq$10 s, whereas hypopnea was defined as $\geq$30 % reduction in airflow for $\geq$10 s associated with an arousal or $\geq$3 % oxygen desaturation. Oxygen desaturation index was calculated by dividing the total number of oxygen desaturation events, where the blood oxygen saturation (SpO_2) dropped to $\geq$4 % below the baseline, by the total number of sleep hours (Ng et al., 2017). Data regarding the participants' age, sex, body mass index (BMI), and neck and waist circumferences were collected from the hospital's medical records.

AHI values of $<$5 and 5–15 indicated non-OSA and mild OSA, respectively (Epstein et al., 2009). POSA was defined as an overall AHI value of $\geq$5 and supine to nonsupine AHI ratio of $\geq$2 (Lee et al., 2017).

2.5. Statistical analysis

AHI, ODI, and arousal index exhibited a positively skewed distribution; therefore, these data are presented in terms of median (25–75th percentile) values. Other sleep parameters and environmental variables showed a near-normal distribution. Differences between patients with different OSA severities in terms of demographical characteristics, polysomnography parameters, and environmental factors were determined through a chi-square test for categorical variables, two-sample t-test for continuous variables with a normal distribution, and Mann–Whitney U test for continuous variables with a skewed distribution.

We previously found that air pollution influenced only mild OSA (He et al., 2022). Therefore, in the present study, a generalized logistic regression model was used to explore the associations of different sleep positions (and time spent in such positions) and air pollution exposure with the risk of mild OSA. When investigating the effects of air pollution on mild OSA, NO_2 and $PM_{2.5}$ were assessed as continuous or dichotomous variables (the third quartile was used as the cutoff point because at this point, the exposure-response curve indicated an increased risk of OSA due to NO_2 exposure). Age, sex, BMI, and neck and waist circumferences were used as covariates to estimate the adjusted odds ratio (OR) and 95 % confidence interval (CI) values for mild OSA, which were compared with the values obtained for patients without OSA. In addition, natural spline adjustments were performed. During the 7-year-long study period, sleep parameters and exposure levels exhibited seasonality and long-term trends (Cassol et al., 2012; Cheng et al., 2019). Therefore, a natural spline with 3 degrees of freedom (*dfs*) per year on the date of participants' visit to our sleep center was included in the model (Qiu et al., 2020). Specifically, the total *dfs* value to adjust for the effects of seasonality and possible long-term trends were 3*7. In addition, a natural spline with 5 *dfs* for exposure to average temperature and relative humidity was included in the model to adjust for the potential nonlinear effects of weather conditions (Shen et al., 2018). The cumulative short-, mid-, and long-term effects of air pollution (lag: 0–1 day, 0–3 days, 0–5 days, 0–7 days, 0–1 month, 0–1 year, and 0–2 years) on OSA were evaluated. Subgroup analyses were performed by stratifying the cohort by age, sex, and BMI; the corresponding OR of mild-OSA associated with an interquartile range (IQR) increment of pollutant was estimated. The chi-square test embedded in the "anova" function by comparing the models fitted with or without an interaction term was performed to

obtain $P_{interaction}$ values.

When investigating the effects of different sleep positions on mild OSA, the duration of sleep in the supine and nonsupine positions was treated continuously or dichotomously (the median value was regarded as the cutoff point because at this point, the exposure-response curve indicated the altered risk of OSA due to prolonged sleep positions).

The exposure-response relationship curves constructed for the associations between different sleep positions and air pollution exposure levels and mild OSA were analyzed using cubic regression splines of each pollutant, defined by a modest-sized set of knots spread evenly throughout covariates, in a generalized additive model adjusted for personal characteristics. This additive model was additionally adjusted for long-term trend, seasonality, relative humidity, and temperature with natural splines when exploring the association between air pollution and mild OSA. Because we investigated the effects of multiple exposure windows, we arbitrarily selected the effects of air pollution at lag (0–5 days) to identify the association between air pollution and mild OSA. The linearity of exposure-response curves was analyzed through a chi-square test embedded in "anova" function by comparing the models fitted with the linear term and those fitted with the smoothing spline function (Abrahamowicz et al., 2003).

Currently, although the widespread report of interactions in the publications, adequate assessment of interaction giving sufficient information to draw conclusions on the size and statistical significance in both additive and multiplicative scale is few (Knol and VanderWeele, 2012). We assessed the interaction effects of sleep position and air pollution on the risk of mild OSA on both additive and multiplicative scales. Additive and multiplicative scales indicate whether the interaction effect of two parameters is stronger (or weaker) than the sum or product of their individual effects, respectively (Knol and VanderWeele, 2012). Relative excess risk due to interaction (RERI), a standard measurement of interaction on the additive scale, is often used to categorize risk factors into different levels (Knol and VanderWeele, 2012). In the present study, two exposure parameters and one outcome variable were assessed as dichotomous variables (the third quartile was used as the cutoff point of air pollution, the median value was used as the cutoff point of sleep duration in a particular position, and the outcome was a binary variable). RERI values of 0, >0, and <0 indicate no interaction, positive additive interaction, and negative additive interaction, respectively (Knol et al., 2011). We further evaluated the interaction effects on the multiplicative scale; a $P_{interaction}$ value of <0.05 and a 95 % CI value not containing 1 indicated statistical significance. The adjusted variables and *dfs* used to adjust for the effects of seasonality and long-term trends were included in the models constructed to evaluate the interaction effects.

All analyses were performed using the "mgcv" package of R (version 4.0.5) to fit generalized linear models and generate exposure-response curves; the package "interactionR" was used to investigate the interaction effects on additive and multiplicative scales.

3. Results

This study included 3330 individuals with or without mild OSA (mean age, 46.43 ± 14.27 years; BMI, 24.27 ± 3.78 kg/m^2). The median AHI value was 5.90 (IQR, 2.20–10.10). Participants with mild OSA were more likely to be men, older, and fatter; their sleep indicators, such as arousal index, ODI, mean SpO_2 level, and minimum SpO_2 level, exhibited a worsening trend (Table 1). However, they had longer total sleep time (both supine and nonsupine) and higher sleep efficiency compared with the participants without OSA. When our participants were divided into POSA and non-POSA groups, patients with POSA were more likely to be men, older, and fatter with worsening sleep indicators. Although patients with POSA had longer total sleep time, they spent more time in the supine position than in a nonsupine position (Supplementary Table 1).

As shown in Fig. 1, the average levels of NO_2 and $PM_{2.5}$ were considerably higher than the guidelines set by the World Health Organization (WHO; Ambient Air Quality Standards for NO_2 and $PM_{2.5}$ were 10 μg/m^3 [5.32 ppb] and 5 μg/m^3, respectively) in 2021 (Burki, 2021).

Table 2 presents the significant associations of short- and long-term NO_2 exposure with the increased risk of mild OSA. Participants exposed to higher NO_2 levels had higher risks of mild OSA than did those exposed to lower NO_2 levels. Compared with participants without OSA, those exposed to higher NO_2 levels had increased risks of mild OSA: the excess

Table 1
Demographic characteristics, sleep-related parameters, and environmental exposures at lag 0 for patients from the sleep center in Taipei.

		Subgroup of patients		
	All patients (*N* = 3330)	Non-OSA (*N* = 1491)	Mild-OSA (*N* = 1839)	*P*-value[b]
Personal characteristics				
Age, years	46.43 ± 14.27	43.60 ± 14.2	48.70 ± 13.9	<0.001
Male, *N* (%)	1720 (51.65)	598 (40.11)	1122 (61.01)	<0.001
BMI, kg/m^2	24.27 ± 3.78	23.20 ± 3.42	25. 20 ± 3.83	<0.001
Neck, cm	35.60 ± 3.39	34.50 ± 3.22	36.50 ± 3.25	<0.001
Waist, cm	84.36 ± 3.15	80.70 ± 9.63	87.30 ± 9.58	<0.001
Sleep-related parameters				
TST, min	279.56 ± 61.92	275.98 ± 66.58	283.13 ± 56.72	0.006
Sleep time with supine position, min	181.92 ± 96.10	179.52 ± 97.02	183.86 ± 95.32	0.194
Sleep time with nonsupine position, min	88.72 ± 75.38	87.96 ± 75.06	89.33 ± 75.65	0.604
Sleep efficiency (%)	76.15 ± 16.87	75.36 ± 17.95	76.79 ± 15.92	0.016
WASO (min)[a]	42.50 (22.40, 79.50)	42.00 (21.00, 84.85)	43.50 (23.00, 75.75)	0.796
AHI (events/h)[a]	5.90 (2.20, 10.10)	1.90 (0.60, 3.30)	9.70 (7.40, 12.20)	<0.001
Arousal index (events/h)[a]	14.10 (9.10, 20.50)	12.70 (8.25, 18.70)	15.60 (10.30, 21.85)	<0.001
ODI (events/h)[a]	4.60 (1.30. 9.45)	1.70 (0.40, 3.70)	9.40 (6.80, 11.90)	<0.001
Mean SpO_2 (%)	96.60 ± 1.37	97.10 ± 1.22	96.2 ± 1.36	<0.001
Minimum SpO_2 (%)	89.93 ± 4.84	92.70 ± 3.14	87.50 ± 4.76	<0.001
Environmental factors				
$PM_{2.5}$ (μg/m^3)	16.02 ± 8.74	16.46 ± 9.07	15.66 ± 8.44	0.009
NO_2 (ppb)	19.53 ± 7.68	19.79 ± 7.66	19.32 ± 7.69	0.077
Temperature (°C)	24.13 ± 5.39	23.95 ± 5.43	24.27 ± 5.35	0.089
Mean RH (%)	71.94 ± 9.09	72.04 ± 9.07	71.85 ± 9.10	0.564

Abbreviations: BMI, body mass index; TST, total sleep time; WASO, wake after sleep onset; AHI, apnea-hypopnea index; ODI, oxygen desaturation index; $PM_{2.5}$, particulate matter with aerodynamic diameter ≤ 2.5 μm; NO_2, nitrogen oxides; RH, relative humidity.

[a] These variables are skewed distributed and described as median (25th, 75th percentiles). Logarithm transformation is performed on them in the test. Other variables are approximately normally distributed and described as mean (standard deviation).

[b] *P*-values are obtained from two-sample *t*-test for continuous variables with normal distribution, Mann-Whitney *U* test for continuous variables with skewed distribution and Chi-square test for categorical variables to compare two OSA subgroups.

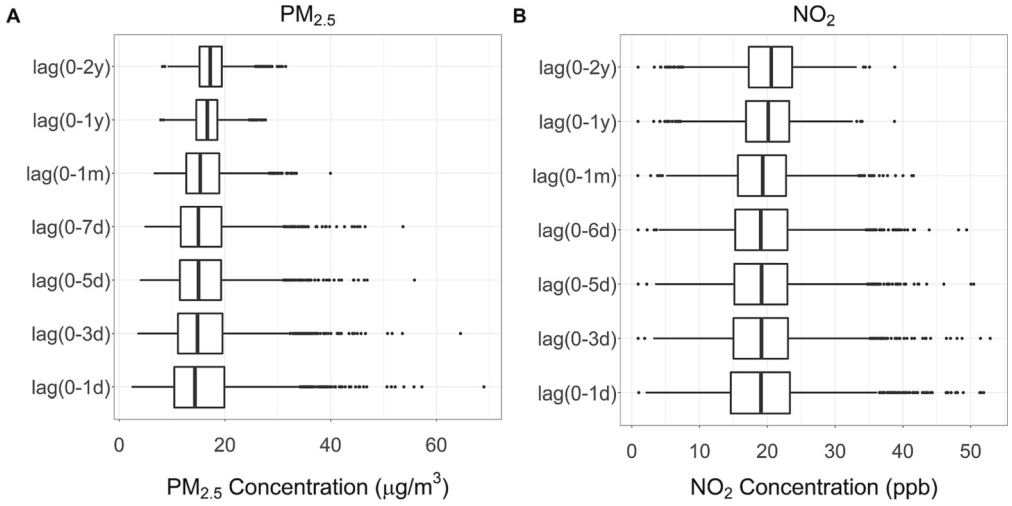


Fig. 1. The distribution of the personal exposure to both short-term and long-term ambient air pollution. Note: d, day; m, month; y, year.

risk of mild OSA was 16.0 % (95 % CI: 3.0 %–30.0 %) per IQR increment in NO_2 exposure level at lag (0–7 days) (7.7 ppb) and 13.0 % (95 % CI: 1.0 %–27.0 %) per IQR increment in average NO_2 exposure level over the previous 2 years (6.4 ppb). When stratified by age, sex, and BMI, only participants with higher BMI values had increased risk of mild OSA associated with an IQR increment of NO_2. The $P_{interaction}$ values for the associations of NO_2 levels at lag (0–5 days), lag (0–7 days), lag (0–1 years), and lag (0–2 years) with BMI were 0.673, 0.687, 0.112, and 0.145, respectively, indicating nonsignificant associations between NO_2 level and mild OSA across participants with different BMI values (Fig. 2). Fig. 3 depicts the exposure-response associations of air pollutants (NO_2 or $PM_{2.5}$) with mild OSA.

As shown in Table 3, participants sleeping for a longer duration in the supine position had a higher risk of mild OSA than did those sleeping for a shorter duration in this position. Especially, the OR of mild-OSA was 1.32 (95 % CI: 1.17, 1.49) compared with those who slept less with supine position (<median); the OR of mild-OSA were 1.20 (95 % CI: 1.03, 1.39) per IQR increment in supine sleep time. Subgroup analyses revealed that participants aged >45 years who slept in the supine position for a longer duration had a significantly higher risk of mild OSA than did younger participants who slept in this position for a short duration (Supplementary Table 2). However, neither the main analysis nor the subgroup analysis revealed any association between the nonsupine position and mild OSA risk (Supplementary Table 2). Fig. 3 illustrates the exposure-response associations of different sleep positions (supine or nonsupine) with mild OSA risk.

Table 4 presents the joint effects of supine and nonsupine sleep duration and NO_2 and $PM_{2.5}$ exposure levels on the risk of mild OSA; participants with low air pollution exposure levels and short sleep duration served as the reference group. No prominent interaction was noted between nonsupine sleep duration and NO_2 exposure level on additive or multiplicative scale in the main analysis. Nevertheless, the interactions between supine sleep duration and NO_2 exposure level at lag (0–7 days), lag (0–1 year), and lag (0–2 years) on both additive and multiplicative scales were significant. The RERI value corresponding to 1-week NO_2 exposure and supine sleep position was 0.63 (95 % CI: 0.10–1.16), indicating that the estimated joint effect on the additive scale for a higher NO_2 exposure level and a longer supine sleep duration was greater than the sum of the individual effects of the aforementioned two parameters. Therefore, a significantly positive interaction effect was noted on the additive scale. The measure of interaction on a multiplicative scale, the ratio of OR, was 1.45 (95 % CI: 1.01–2.07), indicating that the estimated joint effect on this scale for a higher NO_2 exposure level and a longer supine sleep duration was greater than the product of the individual effects of the aforementioned two parameters. Therefore, a significantly positive interaction effect was noted on the multiplicative scale. The RERI values measuring interaction on the additive scale for 1- and 2-year NO_2 exposure and the supine sleep position were 0.56 (95 % CI: 0.13–0.99) and 0.64 (95 % CI: 0.18–1.10), respectively; the corresponding ORs measuring interaction on the multiplicative scale were 1.55 (95 % CI: 1.09–2.22) and 1.60 (95 % CI: 1.12–2.28), respectively. When stratified by sex, the interactions between supine sleep duration and NO_2 exposure level at lag (0–1 year) and lag (0–2 years) were significant on both positive additive and multiplicative scales for men (Supplementary Table 3). Likewise, the interactions between nonsupine sleep duration and NO_2 exposure level at lag (0–1 day), lag (0–1 year), and lag (0–2 years) were significant on both negative additive and multiplicative scales for men (Supplementary Table 4). Age-specific subgroup analyses revealed no prominent interaction between NO_2 exposure level and different sleep positions (Supplementary Tables 5 and 6). For patients with BMI values of >25 kg/m^2, the interactions between supine sleep duration and NO_2 exposure level at lag (0–7 days), lag (0–1 year), and lag (0–2 years) were significant on both positive additive and multiplicative scales (Supplementary Table 7). However, BMI-specific subgroup analyses revealed no significant interaction between nonsupine sleep duration and NO_2 exposure level (Supplementary Table 8).

4. Discussion

To the best of our knowledge, this study is the first to explore the joint association of supine and nonsupine sleep positions with mild OSA. Both short- and long-term NO_2 exposure were significantly associated with an increased risk of mild OSA. A longer supine sleep duration was independently associated with an increased risk of mild OSA; however, nonsupine sleep position was not associated with reduced severity of mild OSA. When supine sleep duration was constant, participants with long-term exposure to high NO_2 levels were likely to have higher ORs for mild OSA than those with long-term exposure to low NO_2 levels. Furthermore, the observed differences were significant; the interactions between supine sleep duration and NO_2 exposure level on both positive additive and multiplicative scales remained significant in men or participants with obesity. However, the joint association of nonsupine sleep position and NO_2 exposure level with mild OSA were nonsignificant on both additive and multiplicative scales. The interaction between nonsupine sleep duration and NO_2 exposure level was significant on both negative additive and negative multiplicative scales for men, indicating the protective benefits of a nonsupine position against the risks of mild OSA due to NO_2 exposure in this specific population.

Sleeping in the supine position can increase the likelihood of upper

Table 2
Odds ratio (OR) and 95 % CI confidence interval (CI) of mild-OSA associated with short- and long-term exposure to air pollutants in patients from Taipei Sleep Center[a] ($N = 3330$).

	Lag (0–1 d)		Lag (0–3 d)		Lag (0–5 d)		Lag (0–7 d)		Lag (0–1 m)		Lag (0–1 y)		Lag (0–2 y)	
	No. events	OR (95 % CI)	No. events	OR (95 % CI)	No. events	OR (95 % CI)	No. events	OR (95 % CI)	No. events	OR (95 % CI)	No. events	OR (95 % CI)	No. events	OR (95 % CI)
NO_2 level (ppb)														
Low (≤75th)	1390	1.00 [Reference]	1383	1.00 [Reference]	1370	1.00 [Reference]	1380	1.00 [Reference]	1409	1.00 [Reference]	1404	1.00 [Reference]	1396	1.00 [Reference]
High (>75th)	449	**1.23 (1.01, 1.50)**	456	**1.32 (1.09, 1.61)**	469	**1.44 (1.18, 1.75)**	459	**1.37 (1.13, 1.67)**	430	1.09 (0.89, 1.33)	435	1.12 (0.93, 1.37)	443	**1.21 (1.01, 1.47)**
Continuous (per IQR NO_2)	1839	1.09 (0.98, 1.22)	1839	**1.12 (1.01, 1.26)**	1839	**1.14 (1.02, 1.29)**	1839	**1.16 (1.03, 1.30)**	1839	1.13 (1, 1.27)	1839	1.11 (0.99, 1.25)	1839	**1.13 (1.01, 1.27)**
$PM_{2.5}$ level (μg/m^3)														
Low (≤75th)	1410	1.00 [Reference]	1416	1.00 [Reference]	1420	1.00 [Reference]	1407	1.00 [Reference]	1425	1.00 [Reference]	1441	1.00 [Reference]	1443	1.00 [Reference]
High (>75th)	429	1.02 (0.83, 1.25)	423	0.98 (0.79, 1.21)	419	0.95 (0.77, 1.18)	432	1.05 (0.85, 1.31)	414	0.98 (0.75, 1.27)	398	0.95 (0.75, 1.20)	396	0.99 (0.77, 1.28)
Continuous (per IQR $PM_{2.5}$)	1839	1.03 (0.91, 1.16)	1839	0.98 (0.86, 1.12)	1839	0.99 (0.86, 1.14)	1839	0.99 (0.86, 1.15)	1839	1.01 (0.84, 1.21)	1839	1.03 (0.87, 1.21)	1839	1.03 (0.87, 1.21)

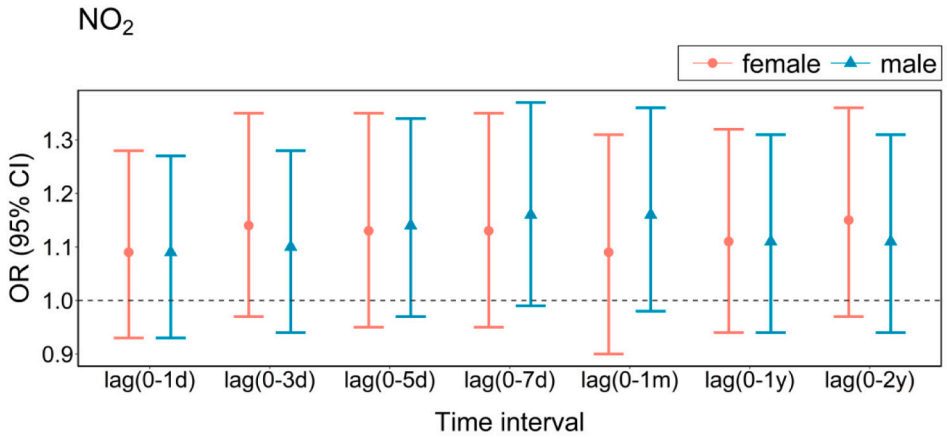
Abbreviations: IQR, interquartile range.
Bold values in the table indicate the significant results with P value < 0.05.
[a] The effects are presented as odds ratio with 95 % CI. The models were fully adjusted for age, sex, BMI, waist and neck circumferences, natural splines of data, humidity and temperature.

airway collapse. It has been well-documented that preventing people from sleep on their back leads to significantly improved upper airway stability and reduces the severity of obstructive events (Cartwright, 1984; Cartwright et al., 1985; de Vries et al., 2015; Kavey et al., 1985; Neill et al., 1997; Oksenberg et al., 2000). A systematic review summarized several studies and concluded that the supine position is a risk factor for OSA in adults (Menon and Kumar, 2013). This finding is consistent with our finding that prolonged supine sleep duration, but not nonsupine sleep duration, was independently associated with the risk of mild OSA. Supine sleep duration was longer in the POSA group than in the non-POSA group; this finding corroborates those of other studies (de Vries et al., 2015; Mador et al., 2005). Therefore, reducing the time spent sleeping in the supine position may help reduce OSA severity (Cartwright, 1984; Cartwright et al., 1985; de Vries et al., 2015; Kavey et al., 1985). A study found a lower AHI value, smaller neck circumference, and lower severity of respiratory anomaly in patients with POSA (Mador et al., 2005). By contrast, we found that the sleep indicators such as arousal index, ODI, mean SpO_2 level, and minimum SpO_2 level exhibited a worse trend in the POSA group than in the non-POSA group. This could be explained by that we derived the POSA subgroup from people with AHI values of <15, therefore, non-POSA patients were those without OSA. However, in other studies, the POSA group comprised patients with all ranges of AHI values.

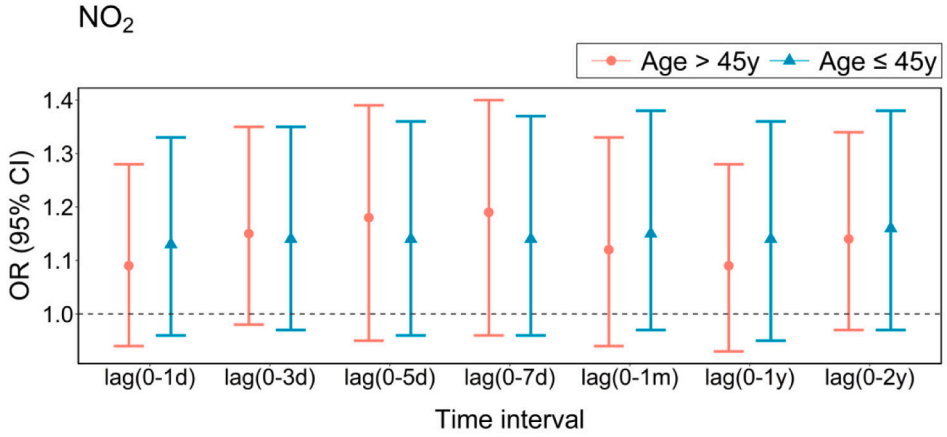
Sleeping in the supine position may exacerbate OSA through the following anatomical and physiological mechanisms. First, the reduction in pharyngeal area due to sleeping in the supine position promotes pharyngeal occlusion (Brown et al., 1987). Second, the blocking of the airway may also be associated with different shapes of the airway: the upper airway is circular in individuals without POSA but elliptical shape in those with POSA; this elliptical shape may adversely affect the muscle activity of the upper airway and increase the likelihood of pharyngeal collapse (Joosten et al., 2015; Leiter, 1996; Walsh et al., 2008). Third, the supine position tends to increase the width and length of uvulas and then shorten the distance between uvula protrusions and the pharyngeal wall, thus resulting in retroglossal airway collapse (Oksenberg and Silverberg, 1998; Yildirim et al., 1991). Fourth, the minimum cross-sectional area of the retropalatal area in the upper airway is larger in patients with POSA than in those without POSA; this may contribute to the increased likelihood of airway collapse (Pevernagie et al., 1995). Finally, the reduction in lung volume due to sleeping in the supine position may increase airway resistance because of the aforementioned factors (Menon and Kumar, 2013). The subgroup analysis performed to explore the association between supine sleep duration and OSA risk revealed a significantly higher risk of OSA in older patients who slept in the supine position for a longer duration. This is consistent with the finding of a study indicating that the pathophysiologic effects of airway collapse due to a specific airway anatomy are considerably stronger in older adults and that these effects are exerted through ineffective airway dilator muscle activity or unstable ventilation control (Eckert et al., 2013; Edwards et al., 2014).

The associations between NO_2 exposure level and mild OSA risk noted in the present study are consistent with our previous finding: short- and long-term NO_2 exposure affect only mild OSA (He et al., 2022). Studies have reported inconsistent results regarding the effects of air pollution on sleep apnea. A Taiwanese study indicated that the annual average levels of $PM_{2.5}$ and NO_2 significantly increase AHI in all patients with sleep disorders (Shen et al., 2018). Another Taiwanese study exploring the effects of the daily average levels of $PM_{2.5}$ and NO_2 on AHI in all patients and patients with severe OSA reported no significant results (Cheng et al., 2019). A US study revealed that exposure to the annual average level of NO_2 influenced moderate to severe OSA; however, this effect was not observed for $PM_{2.5}$ (Billings et al., 2019). Thus, different levels of air pollution and the duration of exposure windows may differentially aggravate OSA. We previously explained in detail the reasons for the observed associations between air pollution and mild OSA (He et al., 2022). Comorbidity burden may progressively

A.



B.



C.

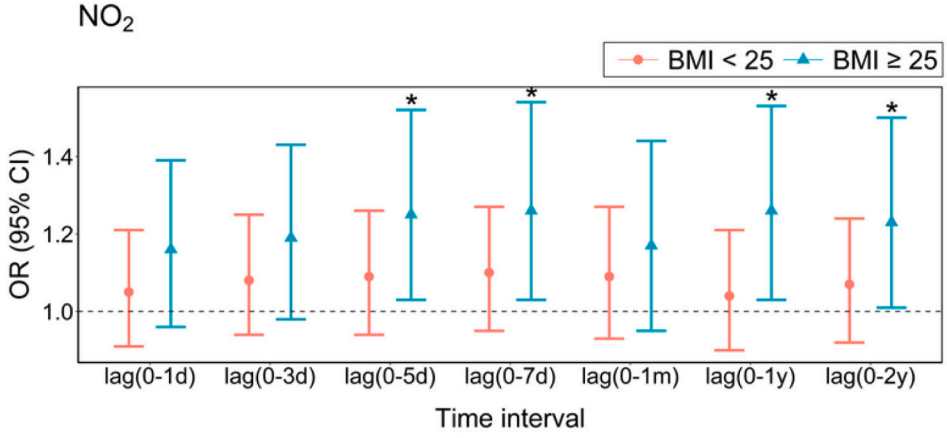


Fig. 2. Odds ratio (95%CI) of mild OSA associated with an IQR increment of personal pollution exposure, compared with non-OSA patients in single-pollutant models by lags stratified by different factors. A. Stratified by gender; B. Stratified by age; C. Stratified by BMI. Generalized logistic regression model was performed while adjusting for the long-term trend, seasonality, weather conditions, and essential characteristics of participants (age, sex, BMI, neck and waist circumference). $P_{interaction}$ values between NO_2 at lag (0-5d), at lag (0–5 d), at lag (0–1 y), and at lag (0—2 y) and different levels of BMI were 0.673, 0.687, 0.112, and 0.145, respectively. Note: IQR, interquartile range; NO_2, nitrogen oxides; d, day; m, month; y, year; * indicates the significance level <0.05.

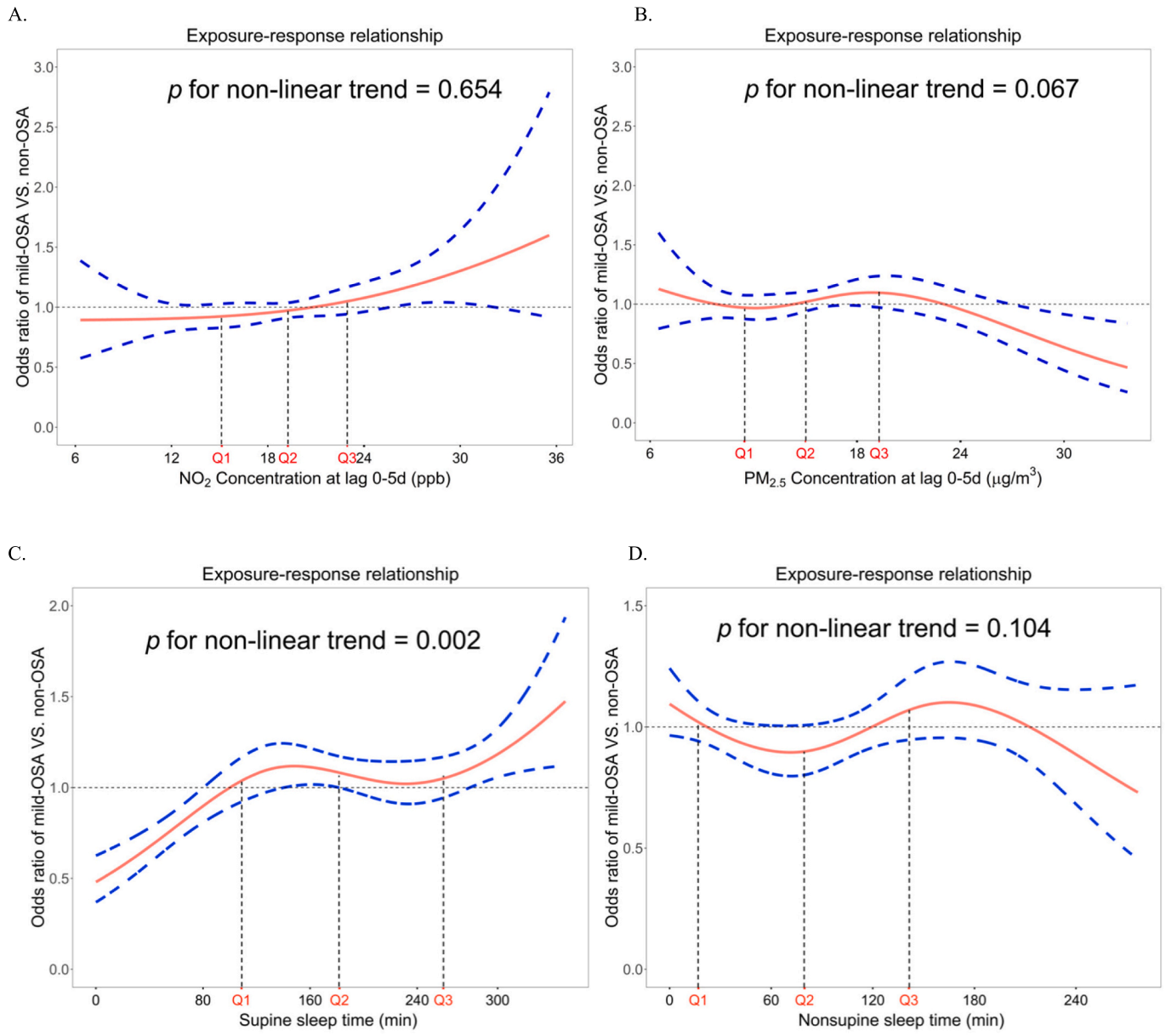


Fig. 3. The exposure-response curves for the relationship between NO_2 exposure, $PM_{2.5}$ exposure, supine posture time as well as side posture time and the odds ratio of mild-OSA, in GAM distributed lag model adjusting for temperature, relative humidity, date, age, gender, BMI, neck circumference, and waist circumferences. Dotted lines represent 95 % CI.

increase with increasing OSA severity (Muxfeldt et al., 2014); thus, obesity and chronic comorbidities strongly contribute to the pathogenesis of moderate to severe OSA, considerably overshadowing the effects of air pollution on OSA. Air pollution leads to OSA primarily by inducing inflammation and oxidative stress in the upper airway (Mehra and Redline, 2008). Then, SpO_2 level may decrease, followed by persistent inflammation, thus resulting in reduced lung ventilation and perfusion. Changes in the central nervous system have been emerged as an alternative possible mechanism for explaining the positive associations found in our study. Inhaled air pollutants may be translocated to the brain through the olfactory nerve (Oberdörster et al., 2004). By inducing neurotoxicity and neuroinflammation, the pollutants penetrating the central nervous system may alter the brain areas involved in the regulation of sleep and ventilation (Calderon-Garciduenas et al., 2016). Furthermore, the pollutants may reduce the level of serotonin, which is a key neurotransmitter essential for the effective modulation of the sleep cycle (Portas et al., 2000). Furthermore, we found that only NO_2 had effects on OSA but not $PM_{2.5}$. Although the literature regarding the specific mechanisms explaining the differential effects of $PM_{2.5}$ and NO_2 on OSA is limited, there are potential explanations that could shed light on this phenomenon. Firstly, NO_2 and $PM_{2.5}$ are distinct air pollutants with different chemical compositions and sizes. While $PM_{2.5}$ is primarily composed of solid and liquid particles, NO_2 is a gaseous pollutant. These differences could result in variations in how they interact with biological systems. NO_2 might have specific pathways or mechanisms through which it affects the respiratory system, leading to the development or exacerbation of OSA. Secondly, air pollutants, including NO_2 and $PM_{2.5}$, can induce inflammation in the respiratory system, which in turn contributes to upper airway dysfunction and increase the risk of OSA. It is possible that NO_2 has a more significant impact on the inflammatory response related to OSA compared to $PM_{2.5}$. Additionally, both NO_2 and $PM_{2.5}$ can generate oxidative stress, which can damage tissues and contribute to the development of respiratory conditions. However, the extent and mechanisms of oxidative stress caused by NO_2 and $PM_{2.5}$ may

Table 3
Odds ratio (OR) and 95 % CI confidence interval (CI) of mild-OSA associated with different sleep positions in patients from Taipei Sleep Center[a] (N = 3330).

	Supine position			Nonsupine position (left + right + prone)	
	No. events	OR (95 % CI)		No. events	OR (95 % CI)
Duration of time			Duration of time		
<Median (0–185.5)	927	1.00 [Reference]	<Median (0–79.7)	901	1.00 [Reference]
≥Median (≥185.6)	912	**1.20 (1.03, 1.39)**	≥Median (≥79.8)	938	1.00 (0.86, 1.16)
Continuous (per IQR supine time)	1839	**1.32 (1.17, 1.49)**	Continuous (per IQR nonsupine time)	1839	0.95 (0.84, 1.08)

Abbreviations: IQR, interquartile range.
Bold values in the table indicate the significant results with P value < 0.05.
[a] The effects are presented as odds ratio with 95 % CI. The models were fully adjusted for age, sex, BMI, waist and neck circumferences.

differ. It is conceivable that NO_2 induces oxidative stress in a manner that specifically influences the pathogenesis of OSA. It is crucial to acknowledge that these potential mechanisms are speculative, and further laboratory research, both in vivo and in vitro, is required to precisely investigate and elucidate the mechanisms underlying the differential effects of $PM_{2.5}$ and NO_2 on OSA.

A novel finding of the present study is the significant interaction effect observed between supine sleep duration and NO_2 exposure level at lag (0–7 days), lag (0–1 year), and lag (0–2 years) on both additive and multiplicative scales (Table 4). Due to the inadequate assessment of the interactions in the existing literature (Knol and VanderWeele, 2012), we attempted to draw conclusions on the size and statistical significance in both additive and multiplicative scales. RERI values of >0 indicate synergism between two parameters (VanderWeele, 2009; VanderWeele and Robins, 2007). We found that the negative effects of prolonged supine sleep duration on mild OSA were significantly modified by the participants' risk of NO_2 exposure, which indicates synergism. The aggravated risks associated with these two parameters might have resulted from a combination of mechanisms, including collapsibility caused by structural alteration of the airway in the supine position, weakened pharyngeal dilator activity, and reduced lung ventilation due to chronic inflammation induced by air pollution.

The interactions between supine sleep duration and NO_2 exposure level at lag (0–1 year) and lag (0–2 years) remained significant on both positive additive and positive multiplicative scales for men (Supplementary Table 3). The effect of posture on the diameter of the upper airway is stronger in men than in women (Huang et al., 1998; Martin et al., 1997). The anatomic differences in the upper airway between the two sexes worsen sleep apnea for men sleeping in the supine position. First, the upper airway muscles of men are less effective in easing airway obstruction than those of women (Jordan et al., 2005). Second, the forward–backward movement of the mandible while sleeping in the supine position is more likely in men, which leads to a decrease in pharyngeal diameter and an increase in upper airway obstruction. By contrast, the pharynx is stable in women, with limited changes in upper airway diameter during mandibular movement (Miyamoto et al., 1999). Although we did not observe any significant interaction effect between the supine position and sex on the risk of mild OSA (Supplementary Table 2), the effects of the supine position are likely to be stronger in men than in women. Consequently, with the addition effect of NO_2, we observed a significant interaction effect between prolonged supine sleep duration and high NO_2 exposure level on mild OSA in men (Supplementary Table 3). This finding indicates a synergistic interaction effect between the anatomic specifications of the upper airway in men and inflammation induced by air pollution on the risk of mild OSA. In BMI-specific subgroup analysis, the interactions between supine sleep duration and NO_2 exposure level at lag (0–7 days), lag (0–1 year), and lag (0–2 years) were significant on both positive additive and positive multiplicative scales in patients with BMI values of >25 kg/m^2(Supplementary Table 7). Obesity is a known risk factor for OSA progression (Duran et al., 2001). In individuals with obesity, fat deposits around the upper airway and thorax (Shelton et al., 1993). These anatomical changes aggravate the collapsibility of the upper airway, which, in turn, decreases lung compliance and functional residual capacity (Naimark and Cherniack, 1960). Although we noted no significant independent effect of NO_2 exposure or supine sleep position on mild OSA in BMI-specific subgroups, the joint exposure of air pollution and supine sleep position significantly increased the risk of mild OSA in participants with obesity.

Although studies have highlighted the benefits of nonsupine sleep position (lateral or prone) for reducing the severity of OSA (Cartwright, 1984; Cartwright et al., 1985; Kavey et al., 1985; Oksenberg et al., 2000), we found no significant results for the independent effect of nonsupine position or the joint effect of nonsupine position and NO_2 exposure on mild OSA. The benefit-risk relationship was noted between nonsupine sleep position and NO_2 exposure in men. A study reported no interaction effect of physical activity and $PM_{2.5}$ exposure on incident dementia on additive or multiplicative scales, which was interpreted as the benefits of exercise outweighing the limited risks of air pollution (Ran et al., 2021). Nevertheless, we eliminated the possibility that the benefits of nonsupine position outweigh the limited risk of NO_2 exposure because we found no significant independent effect of nonsupine position on mild OSA. We speculate that the benefits of nonsupine sleep position are far less than the risk of NO_2 exposure, which might have resulted in the null joint association. Furthermore, it is reasonable that pathogenic factors contributing to OSA are so intricate that changing sleep position alone may not benefit the general population.

The present study has the following strengths. First, we used a land use regression model with spatiotemporal adjustment to accurately estimate the level of each participant's personal exposure to air pollution. Second, we comprehensively evaluated the interaction effects on both additive and multiplicative scales. Furthermore, we investigated the interaction effects of both short- and long-term NO_2 exposure and different sleep positions on the risk of mild OSA to avoid obtaining significant results by chance. Our study has some limitations. First, we collected the AHI data once from all the individuals visiting our sleep center at different times rather than collecting the data at multiple visits to reflect variations. Second, the cross-sectional design of this study limited the possibility of causal inference. Additionally, attaching polysomnography equipment during sleep may affect the sleep position of individuals, thus affecting the severity of apnea. Selection bias could not be avoided in the current study design. Finally, it is important to note that our study did not specifically address the issue of exposure to indoor air pollution, despite its recognized significance as a factor that can significantly impact health outcomes.

5. Conclusions

In this population-based study, we found that a longer supine sleep duration and a higher NO_2 exposure level were independently associated with a higher risk of mild OSA. Significant interaction effects between supine sleep position and long-term NO_2 exposure on mild OSA were observed on both positive additive and positive multiplicative scales, which persisted after sex- and BMI-specific subgroup analyses. However, we found no interaction effect of nonsupine sleep position and NO_2 exposure on the risk of mild OSA. Nonetheless, the benefits of a nonsupine sleep position outweighed the risks of long-term NO_2 exposure in men. It is a hint to specific populations that avoidance of prolonged supine sleep position may reduce the risk of mild OSA caused by personal exposure to high levels of NO_2.

Table 4
Additive and multiplicative interaction effects between sleep time with supine/nonsupine sleep position and exposure to NO_2 on different lags on mild-OSA in patients from Taipei Sleep Center Population[a] (N = 3330).

	Low NO_2 (<75th)		High NO_2 (≥75th)		RERI[b]	Multiplicative scale[c]	$P_{interaction}$[c]
	No. events	OR (95 % CI)	No. events	OR (95 % CI)			
Lag (0–1 d)							
Duration of supine time							
<Median (0–185.5)	715	1.00 [Reference]	212	1.17 (0.90, 1.54)			0.640
≥Median (≥185.6)	675	1.24 (1.03, 1.48)	237	1.58 (1.22, 2.05)	0.17 (−0.30. 0.64)	1.09 (0.76, 1.56)	
Duration of nonsupine time							
<Median (0–79.7)	676	1.00 [Reference]	225	1.31 (1.01, 1.70)			0.472
≥Median (≥79.8)	714	1.02 (0.85, 1.22)	224	1.17 (0.90, 1.52)	−0.16 (−0.59, 0.27)	0.88 (0.61, 1.25)	
Lag (0–3 d)							
Duration of supine time							
<Median (0–185.5)	699	1.00 [Reference]	228	1.21 (0.93, 1.59)			0.323
≥Median (≥185.6)	684	1.22 (1.02, 1.46)	228	1.78 (1.36, 2.33)	0.34 (−0.16, 0.85)	1.20 (0.84, 1.72)	
Duration of nonsupine time							
<Median (0–79.7)	675	1.00 [Reference]	226	1.50 (1.15, 1.95)			0.163
≥Median (≥79.8)	708	1.04 (0.87, 1.25)	230	1.21 (0.93, 1.58)	−0.33 (−0.80, 0.14)	0.78 (0.54, 1.11)	
Lag (0–5 d)							
Duration of supine time							
<Median (0–185.5)	690	1.00 [Reference]	237	1.31 (1.01, 1.71)			0.265
≥Median (≥185.6)	680	1.22 (1.02, 1.46)	232	1.97 (1.50, 2.58)	0.43 (−0.12, 0.98)	1.23 (0.86, 1.75)	
Duration of nonsupine time							
<Median (0–79.7)	672	1.00 [Reference]	229	1.56 (1.19, 2.03)			0.373
≥Median (≥79.8)	698	1.01 (0.85, 1.21)	240	1.34 (1.03, 1.74)	−0.23 (−0.72, 0.27)	0.85 (0.59, 1.22)	
Lag (0–7 d)							
Duration of supine time							
<Median (0–185.5)	701	1.00 [Reference]	226	1.15 (0.88, 1.50)			0.042
≥Median (≥185.6)	679	1.17 (0.98, 1.40)	233	1.96 (1.49, 2.57)	0.63 (0.10, 1.16)	1.45 (1.01, 2.07)	
Duration of nonsupine time							
<Median (0–79.7)	674	1.00 [Reference]	227	1.47 (1.13, 1.91)			0.454
≥Median (≥79.8)	706	1.01 (0.84, 1.20)	232	1.29 (0.99, 1.68)	−0.68 (−0.65, 0.28)	0.87 (0.61, 1.25)	
Lag (0–1 m)							
Duration of supine time							
<Median (0–185.5)	724	1.00 [Reference]	203	0.95 (0.73, 1.25)			0.140
≥Median (≥185.6)	685	1.19 (1.00, 1.43)	227	1.49 (1.14, 1.94)	0.34 (−0.08, 0.76)	1.31 (0.92, 1.87)	
Duration of nonsupine time							
<Median (0–79.7)	684	1.00 [Reference]	217	1.18 (0.90, 1.54)			0.394
≥Median (≥79.8)	725	1.01 (0.85, 1.21)	213	1.02 (0.78, 1.33)	−0.17 (−0.56, 0.22)	0.86 (0.60, 1.22)	
Lag (0–1 y)							
Duration of supine time							
<Median (0–185.5)	723	1.00 [Reference]	204	0.90 (0.69, 1.18)			0.013
≥Median (≥185.6)	681	1.15 (0.96, 1.38)	231	1.61 (1.24, 2.10)	0.56 (0.13, 0.99)	1.55 (1.09, 2.22)	
Duration of nonsupine time							
<Median (0–79.7)	682	1.00 [Reference]	219	1.21 (0.93, 1.57)			0.422
≥Median (≥79.8)	722	1.01 (0.84, 1.20)	216	1.05 (0.81, 1.37)	−0.16 (−0.56, 0.23)	0.87 (0.61, 1.23)	
Lag (0–2 y)							
Duration of supine time							
<Median (0–185.5)	722	1.00 [Reference]	205	0.96 (0.73, 1.24)			0.010
≥Median (≥185.6)	674	1.13 (0.95, 1.36)	238	1.73 (1.33, 2.25)	0.64 (0.18, 1.10)	1.60 (1.12, 2.28)	
Duration of nonsupine time							
<Median (0–79.7)	675	1.00 [Reference]	226	1.35 (1.04, 1.74)			0.236
≥Median (≥79.8)	721	1.02 (0.85, 1.22)	217	1.11 (0.85, 1.44)	−0.26 (−0.69, 0.17)	0.81 (0.57, 1.15)	

Abbreviations: RERI, relative excess risk due to interaction.

[a] The effects are presented as odds ratio with 95 % CI, with participants with low air pollution exposure level and low duration of supine/nonsupine sleep time as the reference group. The models were fully adjusted for age, sex, BMI, waist and neck circumferences, natural splines of data, humidity and temperature.

[b] A RERI < 0 indicates negative additive interaction or joint excess risk < sum of individual excess risk; A RERI = 0 indicates no additive interaction or joint excess risk = sum of individual excess risk; A RERI > 0 indicates positive additive interaction or joint excess risk > sum of individual excess risk.

[c] The P-value for interaction <0.05 or 95 % CI of multiplicative scale not containing 1 indicates the existence of multiplicative interaction.

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CRediT authorship contribution statement

Yansu He: Data curation, Formal analysis, Writing – original draft preparation, Writing – review & editing. Wen-Te Liu: Writing – review & editing. Shang-Yang Lin: The integrity and accuracy of the data. Zhiyuan

Li: The application of the land-use regression and the accuracy of the exposure assessment. Hong Qiu: The integrity and accuracy of the data. Steve Huang-Lam Yim: The application of the land-use regression and the accuracy of the exposure assessment. Hsiao-Chi Chuang: Writing – review & editing, Methodology. Kin Fai Ho: Conceptualization, Methodology, Supervision, Writing - review & editing, Project administration, Funding acquisition.

Declaration of competing interest

The authors 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

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.166531.

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