

Effects of short-term air pollution exposure on respiratory infection-related healthcare burden in kidney transplant recipients

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ABSTRACT

Objective: Kidney transplant recipients are highly susceptible to respiratory tract infections (RTIs), and short-term exposure to ambient air pollution may aggravate their clinical outcomes. However, evidence regarding the effects of specific pollutants on hospitalization burden in this population remains limited. This study aims to investigate the effects of pollutants such as PM_{2.5} on hospitalization burden after RTIs in kidney transplant recipients.

Methods: This retrospective time-series study included 874 kidney transplant recipients who were hospitalized for RTIs at the Third Xiangya Hospital of Central South University between 2017 and 2023. High-resolution environmental data were used to assess daily exposure to 6 ambient air pollutants, namely PM_{2.5}, PM₁₀, SO₂, NO₂, CO, and O₃, within the 7 days before the onset of RTI symptoms. Distributed lag non-linear models (DLNMs) were applied to evaluate pollutant-specific lagged and cumulative associations between the 6 ambient air pollutants and hospitalization costs and length of hospital stay, with adjustment for meteorological conditions and individual-level variables.

Results: PM_{2.5} showed the most significant association with hospitalization burden. At a cumulative exposure level of 160 µg/m³, hospitalization costs increased by 9 544.5 yuan (95% CI 2 548.8 to 21 637.7). When PM_{2.5} exposure reached 200 µg/m³ on lag day 0, it was associated with prolonged hospital stay and increased hospitalization costs. PM₁₀ showed a trend toward dose-dependent cumulative effect on length of hospital stay, with a relative risk of 1.63 at 300 µg/m³ (95% CI 0.18 to 15.94). SO₂ levels above 75 µg/m³ were also associated with increased hospitalization burden. In contrast, no consistent or significant associations were observed for CO, NO₂, or O₃.

Conclusion: Short-term exposure to higher levels of PM_{2.5}, PM₁₀, and SO₂ significantly

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increases the clinical and economic burden of RTIs in kidney transplant recipients. These findings highlight the importance of developing targeted air pollution prevention and control strategies to protect susceptible patient populations.

KEY WORDS kidney transplant recipients; ambient air pollution; PM_{2.5}; respiratory tract infection; healthcare burden

短期空气污染暴露对肾移植受者呼吸系统感染相关医疗负担的影响

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[摘要] 目的: 肾移植受者极易发生呼吸道感染(respiratory tract infections, RTIs), 短期暴露于环境空气污染可能会加重其临床结局。然而, 目前关于特定污染物对该人群住院负担影响的证据仍然有限。本研究旨在探讨PM_{2.5}等污染物对肾移植患者RTIs后住院负担的影响。**方法:** 本研究为一项回顾性时间序列研究, 共纳入了2017至2023年因RTIs住院至中南大学湘雅三医院的874例肾移植受者。利用高分辨率环境数据评估患者RTIs症状出现前7 d内6种环境空气污染物(PM_{2.5}、PM₁₀、SO₂、NO₂、CO和O₃)的每日暴露情况。应用分布滞后非线性模型(distributed lag non-linear models, DLNMs)评估6种环境空气污染物与住院费用和住院时长的特异性滞后关联和累积关联, 并对气象条件和个体层面的变量进行调整。**结果:** PM_{2.5}与住院负担的关联最为显著, 在PM_{2.5}浓度为160 μg/m³时, 其预测累积效应对应的住院费用增加了9 544.5元(95% CI 2 548.8~21 637.7); 在滞后第0天暴露达200 μg/m³时, PM_{2.5}与住院时间延长及费用增加相关。PM₁₀对住院时长呈剂量依赖性的累积效应趋势, 在300 μg/m³时相对危险度为1.63(95% CI 0.18~15.94)。当SO₂水平超过75 μg/m³时, 同样与住院负担增加相关。而CO、NO₂及O₃未观察到一致或显著的相关性。**结论:** 短期暴露于较高水平的PM_{2.5}、PM₁₀和SO₂会显著增加肾移植受者合并RTIs的临床和经济负担。这些发现强调了制订针对性空气污染防控策略以保护易感患者群体的重要性。

[关键词] 肾移植受者; 环境空气污染; PM_{2.5}; 呼吸道感染; 医疗负担

Respiratory tract infections are a leading cause of hospitalization in solid organ transplant recipients, including kidney transplant patients. Immunosuppressive therapy and compromised pulmonary defenses significantly increase susceptibility to environmental exposures in this population^[1]. Among these exposures, ambient air pollution represents a growing concern, with mounting evidence linking it to adverse respiratory and systemic outcomes. Transplant recipients, already immunocompromised, may be particularly vulnerable to the health effects of polluted air. Recognizing these risks, the World Health Organization (WHO) released updated Global Air Quality Guidelines in 2021, setting strict 24-hour mean thresholds: PM_{2.5}≤15 μg/m³, PM₁₀≤

45 μg/m³, O₃ (8-hour) ≤100 μg/m³, SO₂≤40 μg/m³, NO₂≤25 μg/m³, and CO≤4 mg/m³^[2]. In contrast, the Chinese GB3095-2012^[3] standard allows higher daily exposure limits: PM_{2.5}≤35 μg/m³ (Grade I) and 75 μg/m³ (Grade II); PM₁₀≤50 and 150 μg/m³; SO₂≤50 and 150 μg/m³; NO₂≤80 μg/m³; O₃≤100 and 160 μg/m³; CO≤4 mg/m³.

PM_{2.5} is particularly hazardous due to its ability to penetrate deep into the alveoli and enter the systemic circulation, triggering a cascade of biological effects^[4-5]. Global burden estimates attribute millions of premature deaths each year to PM_{2.5} exposure, primarily through respiratory and cardiovascular pathways^[6-9]. Epidemiological studies have consistently shown that even short-term increases in PM_{2.5} concentrations are

associated with exacerbations of asthma^[10] and chronic obstructive pulmonary disease (COPD)^[11], increased risk of pneumonia, and other acute respiratory infections^[12]. These effects are not limited to high pollution levels—adverse outcomes have been reported even at concentrations below regulatory thresholds^[13]. Beyond respiratory morbidity, PM_{2.5} exposure is also linked to cardiovascular events, including ischemic heart disease, arrhythmias, hypertension, stroke, and heart failure^[6]. Mechanistic studies^[14–16] implicate oxidative stress, systemic inflammation, endothelial dysfunction, and autonomic imbalance as key biological pathways. Transplant recipients, especially those with kidney grafts, are uniquely vulnerable to these environmental hazards^[17]. The combined immunosuppression, pre-existing comorbidities, and post-operative fragility compound their risk for pollution-related complications^[18]. Despite this, few studies have explored the short-term impacts of air pollution—particularly PM_{2.5}—on hospitalization outcomes such as medical costs and length of stay in this immunocompromised population.

Distributed lag non-linear models (DLNMs) offer a robust statistical framework for examining delayed and non-linear effects of environmental exposures on health outcomes^[19]. DLNMs have been widely applied to assess air pollution-related mortality and emergency visits in the general population^[20–22], but their use in evaluating post-transplant hospitalization metrics remains limited.

This study aims to investigate the short-term associations between ambient air pollutants (PM_{2.5}, PM₁₀, O₃, SO₂, NO₂, CO) and hospitalization outcomes—including total cost and length of stay—among kidney transplant recipients admitted for respiratory tract infections. A DLNM approach was used to assess both lag-specific and cumulative effects of pollutant exposure during the 7 days prior to symptom onset.

1 Participants and methods

1.1 Ethics statement

This study was approved by the Ethics Committee of the Third Xiangya Hospital of Central South University (Approval number: 22294). The study was conducted in accordance with the ethical principles

outlined in the Declaration of Helsinki. All participants were informed about the purpose of the study, assured of confidentiality, and provided written consent prior to participation. Participation was voluntary, and respondents could withdraw at any time without penalty.

1.2 Participants and data collection

We conducted a retrospective time-series study among kidney transplant recipients admitted to the Third Xiangya Hospital of Central South University between 2017 and 2023 due to respiratory tract infections. For each patient, the date of symptom onset was determined based on clinical complaints and was linked—along with the residential address—to local environmental monitoring data. In addition to environmental exposure variables, we collected detailed patient-level information, including age, sex, body mass index (BMI), education level, chief syndrome, documented complications, admission and discharge dates, and total hospitalization cost.

Patient residential addresses were first geocoded using the Google Maps API to obtain precise latitude and longitude coordinates. Daily concentrations of 6 ambient air pollutants—PM_{2.5}, PM₁₀, O₃, SO₂, NO₂, and CO—were obtained from the ChinaHighPM2.5: High-resolution and High-quality Ground-level PM_{2.5} Dataset for China (2000–2023)^[23]. For each pollutant, daily exposure values from the day of symptom onset (lag 0) to 7 days prior (lag days 0 to 7) were compiled. Meteorological data, including daily mean temperature and relative humidity, were retrieved from the NASA POWER API (<https://power.larc.nasa.gov>) and matched to each patient's location and time frame.

1.3 Outcome measures

The primary outcomes were total hospitalization cost [measured in Chinese Yuan (CNY)] and length of hospital stay (in days). Hospitalization cost was treated as a continuous variable and modeled using a Gaussian family, while length of stay, characterized as count data with potential overdispersion, was modeled using a quasi-Poisson family.

1.4 Statistical analysis

Data processing and analysis were performed using Python 3.9 (with libraries such as pandas, xarray, netCDF4, datetime, openpyxl, etc.) and R 4.4.2

(including the *dlm* package and other relevant packages). Continuous variables with a normal distribution are presented as mean±standard deviation. Categorical variables were presented as frequencies (percentages). DLNMs were used to characterize the association between each pollutant and hospitalization outcomes, accounting for non-linear exposure-response and lag-response relationships. The exposure-response function was modeled using B-splines, and the lag-response function was modeled using a natural cubic spline over lag days 0 to 7. For each pollutant, a cross-basis matrix was created using the *crossbasis* function from the R *dlm* package^[19]. The regression models adjusted for potential confounders, including age, sex, BMI, natural spline functions for temperature and humidity (each with 3 degrees of freedom), day of the week (DOW), and holiday indicator.

The model for hospitalization cost was specified as a generalized linear model with a Gaussian distribution: $E(Y_i) = \beta_0 + \text{cb}(\text{Pollutant } 0-7, i) + \beta_1 \cdot \text{age}_i + \beta_2 \cdot \text{Sex}_i + \beta_3 \cdot \text{BMI}_i + f_1(\text{Temperature}_i) + f_2(\text{Humidity}_i) + \text{DOW}_i + \text{Holiday}_i$. Where $\text{cb}(\text{Pollutant } 0-7, i)$ denotes the cross-basis function capturing the non-linear and lagged effects of air pollutant exposure, and f_1 and f_2 represent natural spline functions for temperature and humidity, respectively. A similar model was fitted for hospital stay duration using a quasi-Poisson distribution to account for overdispersion. Cumulative and lag-specific *RR* and 95% *CI* were estimated for increasing concentrations of each pollutant, using the following reference values based on the Chinese National Ambient Air Quality Standards (GB 3095-2012): 35 $\mu\text{g}/\text{m}^3$ for $\text{PM}_{2.5}$, 50 $\mu\text{g}/\text{m}^3$ for PM_{10} , 50 $\mu\text{g}/\text{m}^3$ for SO_2 , 80 $\mu\text{g}/\text{m}^3$ for NO_2 , 100 $\mu\text{g}/\text{m}^3$ for O_3 , and 1 mg/m^3 for CO .

2 Results

A total of 874 kidney transplant recipients hospitalized for respiratory tract infections were included in the analysis. The age was (43.93±11.07) years, and 341 patients (39.02%) were female. The BMI was (21.84±3.24) kg/m^2 . Among the cohort, the most common presenting symptom was cough (67.51%), followed by fever (52.75%) and chest distress (15.10%). Regarding education, the majority of patients had

completed high school (55.83%), followed by university education (38.22%) and elementary school (5.95%). In terms of comorbidities, 9.73% had diabetes, 30.21% had hypertension, 2.86% had coronary heart disease (CHD), and 0.34% had a history of stroke. Most admissions occurred during winter (37.30%), followed by spring (23.11%), summer (20.02%), and autumn (19.57%; Table 1).

On case days, the concentration of $\text{PM}_{2.5}$ was (41.29±26.02) $\mu\text{g}/\text{m}^3$, with a range of 4.40 to 185.80 $\mu\text{g}/\text{m}^3$. PM_{10} was (63.69±35.62) $\mu\text{g}/\text{m}^3$, ranging from 9.70 to 241.10 $\mu\text{g}/\text{m}^3$. Among the gaseous pollutants, the values were 2.60 to 52.20 (10.31±4.88) $\mu\text{g}/\text{m}^3$ for SO_2 , 0.26 to 1.77 (0.91±0.24) mg/m^3 for CO , 5.10 to 89.90 (26.51±14.21) $\mu\text{g}/\text{m}^3$ for NO_2 , and 7.40 to 231.30 (88.75±40.3) $\mu\text{g}/\text{m}^3$ for O_3 . Meteorological conditions also varied substantially, with a mean temperature of −4.53 to 32.94 (15.55±9.25) °C and a relative humidity of 42.12% to 95.56% (80.06±10.08%; Table 2).

Based on a reference level of $\text{PM}_{2.5}$ =35 $\mu\text{g}/\text{m}^3$, we examined changes in hospitalization costs and length of stay among kidney transplant recipients who developed respiratory tract infections, across varying $\text{PM}_{2.5}$ concentrations and lag days. At lag day 0, higher $\text{PM}_{2.5}$ concentrations—particularly at 200 $\mu\text{g}/\text{m}^3$ —were associated with increased hospitalization cost and duration (Figure 1A and 1B). However, isolated lag effects beyond day 0 were less pronounced (Figure 1A and 1B). In contrast, cumulative effects were more substantial. At $\text{PM}_{2.5}$ =160 $\mu\text{g}/\text{m}^3$, the cumulative effect at lag day 1 showed an increase in hospitalization cost of 9 544.5 yuan (95% *CI* 2 548.8 to 21 637.7), with this upward trend becoming more evident at higher concentrations (Figure 1C). For hospitalization duration, cumulative *RR*s at lag days 0 and 1 rose consistently with increasing $\text{PM}_{2.5}$ levels, whereas lag days 6 and 7 showed minimal or even inverse effects (Figure 1D). Overall, the impact of $\text{PM}_{2.5}$ on both hospitalization cost and duration was more pronounced at higher concentrations, while short-term fluctuations within the national Grade I standard threshold ($\leq 35 \mu\text{g}/\text{m}^3$) had limited influence. At extremely elevated levels, such as 200 $\mu\text{g}/\text{m}^3$, exposure on lag day 0 markedly increased both clinical and economic burdens (Figure 1E and 1F).

Table 1 Clinical characteristics of patients

Variables	Values
Age/Years	43.93±11.07
Female/[No.(%)]	341(39.02)
BMI/(kg·m ⁻²)	21.84±3.24
Syndrome/[No.(%)]	
Cough	590(67.51)
Fever	461(52.75)
Chest distress	132(15.10)
Education level/[No.(%)]	
University	334(38.22)
High school	488(55.83)
Elementary school	52(5.95)
Complications/[No.(%)]	
Diabetes	85(9.73)
Hypertension	264(30.21)
CHD	25(2.86)
Stroke	3(0.34)
Season/[No.(%)]	
Spring	202(23.11)
Summer	175(20.02)
Autumn	171(19.57)
Winter	326(37.30)
Length of hospital stay/Days	11.11±7.42

Continuous variables with a normal distribution are presented as mean±standard deviation. Categorical variables are presented as frequencies (percentages). BMI: Body mass index; CHD: Coronary heart disease.

The effects of PM₁₀ on hospitalization costs and length of stay were both showing a slight decrease at lag

day 7 at 50–250 µg/m³ (Figure 2A and 2B). However, when examining cumulative effects, a clearer pattern emerged: at lag day 5, elevated PM₁₀ levels were associated with the cost (Figure 2C and 2D) and notably increased in hospitalization duration. Specifically, at PM₁₀=250 µg/m³, the *RR* for hospital stay was 1.12 (95% *CI* 0.34 to 3.72), and this rose to 1.63 (95% *CI* 0.18 to 15.94) at PM₁₀=300 µg/m³ (Figure 2D). When considering both lag structure and exposure concentration, PM₁₀ values below 150 µg/m³ appeared to have limited impact on hospitalization outcomes. However, once PM₁₀ exceeded the national Grade II standard (150 µg/m³), both hospitalization cost and duration began to increase substantially (Figure 2E and 2F), except for lag 0.

The Grade I standard for SO₂ is 50 µg/m³. When SO₂ concentrations remained below this threshold, the trends in hospitalization cost and duration showed some fluctuations (Figure 3A and 3B). However, when SO₂ reached higher concentrations — particularly above 75 µg/m³—its cumulative effect on hospitalization duration became more pronounced (Figure 3C), and hospitalization costs also increased across most lag days, except for lag 0 and lag 7 (Figure 3D). When SO₂ levels were below 50 µg/m³, the effects on both outcomes were minimal. In contrast, once concentrations exceeded this threshold, the impact on hospitalization burden became substantially more evident (Figure 3E and 3F).

Table 2 Distribution of daily air pollution exposure levels on case days

Variables	Mean ± standard deviation	Range	25th Percentile	Median	75th Percentile
PM _{2.5} /(µg·m ⁻³)	41.29±26.02	4.40 to 185.80	22.52	34.50	53.35
PM ₁₀ /(µg·m ⁻³)	63.69±35.62	9.70 to 241.10	36.80	55.50	82.80
SO ₂ /(µg·m ⁻³)	10.31±4.88	2.60 to 52.20	7.10	9.10	12.20
CO/(mg·m ⁻³)	0.91±0.24	0.26 to 1.77	0.73	0.86	1.06
NO ₂ /(µg·m ⁻³)	26.51±14.21	5.10 to 89.90	16.20	22.40	33.10
O ₃ /(µg·m ⁻³)	88.75±40.33	7.40 to 231.30	58.60	85.80	114.10
Temperature/°C	15.55±9.25	−4.53 to 32.94	7.53	15.23	24.16
Humidity/%	80.06±10.08	42.12 to 95.56	74.94	82.44	87.88

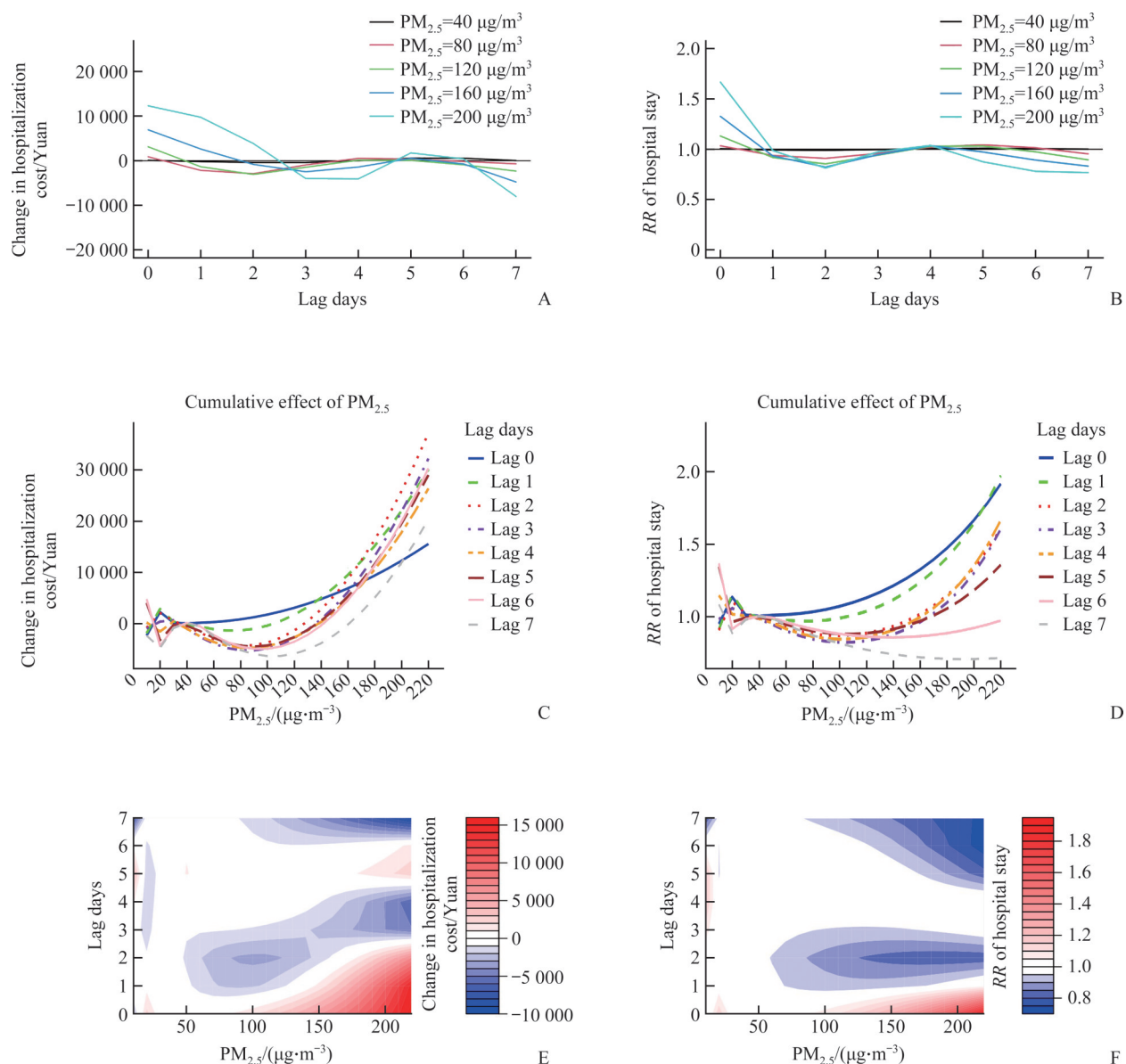


Figure 1 Associations between short-term $PM_{2.5}$ exposure and hospitalization outcomes among kidney transplant recipients with respiratory tract infections

A and B: Lag-response associations between $PM_{2.5}$ exposure at selected concentrations and changes in hospitalization cost (A) and the relative risk of prolonged hospital stay (B) for lag 0–7 days. C and D: Cumulative exposure-response curves showing the association between $PM_{2.5}$ concentration and changes in hospitalization cost (C) and the relative risk of prolonged hospital stay (D) for lag 0–7 days. E and F: Exposure-lag-response contour plots showing the association between $PM_{2.5}$ exposure and the relative risk of hospitalization cost across different lag periods (E) and the joint effects of $PM_{2.5}$ concentration and lag days on the relative risk of prolonged hospital stay (F). All models were adjusted for age, sex, body mass index, temperature, relative humidity, day of the week, and holidays.

For CO , NO_2 , and O_3 , no consistent or robust short-term associations with hospitalization cost or duration were observed. While the cumulative exposure-response curve for CO suggested a possible increase in hospitalization cost at concentrations exceeding 2.0 mg/m^3 —particularly at lag days 0 and 1—the lag-

specific effects remained generally flat, and the impact on hospitalization duration was limited to a delayed increase around lag day 6 (Supplementary Figure 1, <https://doi.org/10.57760/sciencedb.xbyxb.00175>). For NO_2 , both lag-specific and cumulative effects showed minimal and inconsistent variation across concentration

ranges, with wide confidence intervals and no clear dose-response pattern (Supplementary Figure 2, <https://doi.org/10.57760/sciencedb.xbyxb.00175>). Similarly, exposure to O_3 across a wide range of concentrations ($50\text{--}250\text{ }\mu\text{g}/\text{m}^3$) was not associated with meaningful changes in either hospitalization cost or duration (Supplementary

Figure 3, <https://doi.org/10.57760/sciencedb.xbyxb.00175>).

Overall, these findings suggest that short-term exposure to CO , NO_2 , and O_3 may not exert a stable or clinically significant influence on hospitalization burden in this study population.

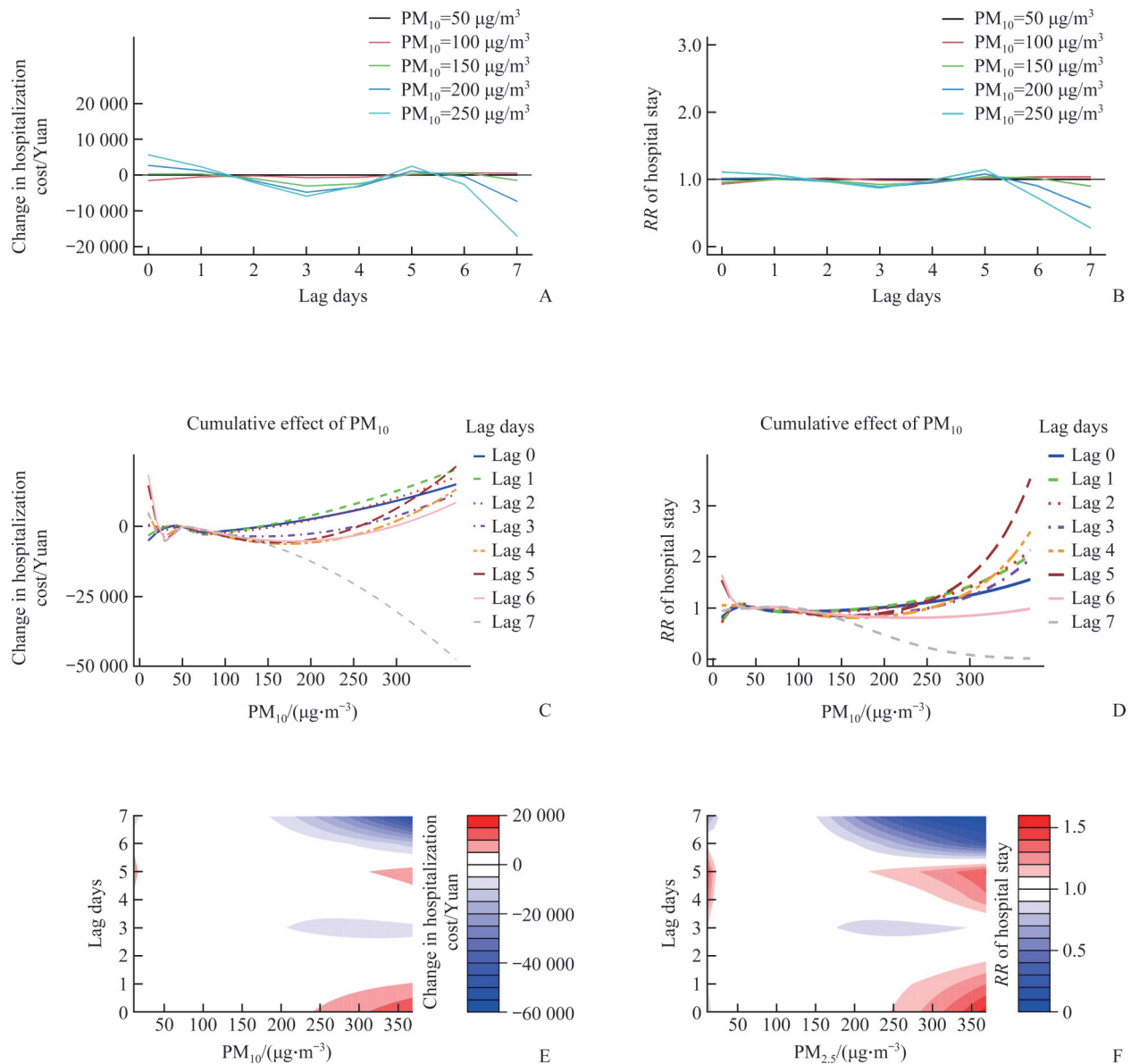


Figure 2 Associations between short-term PM_{10} exposure and hospitalization outcomes among kidney transplant recipients with respiratory tract infections

A and B: Lag-response associations between PM_{10} exposure at selected concentrations and changes in hospitalization cost (A) and the relative risk of prolonged hospital stay (B) for lag 0–7 days. C and D: Cumulative exposure-response curves showing the association between PM_{10} concentration and changes in hospitalization cost (C) and the relative risk of prolonged hospital stay (D) for lag 0–7 days. E and F: Exposure-lag-response contour plots showing the association between PM_{10} exposure and the relative risk of hospitalization cost across different lag periods (E) and the joint effects of PM_{10} concentration and lag days on the relative risk of prolonged hospital stay (F). All models were adjusted for age, sex, body mass index, temperature, relative humidity, day of the week, and holidays.

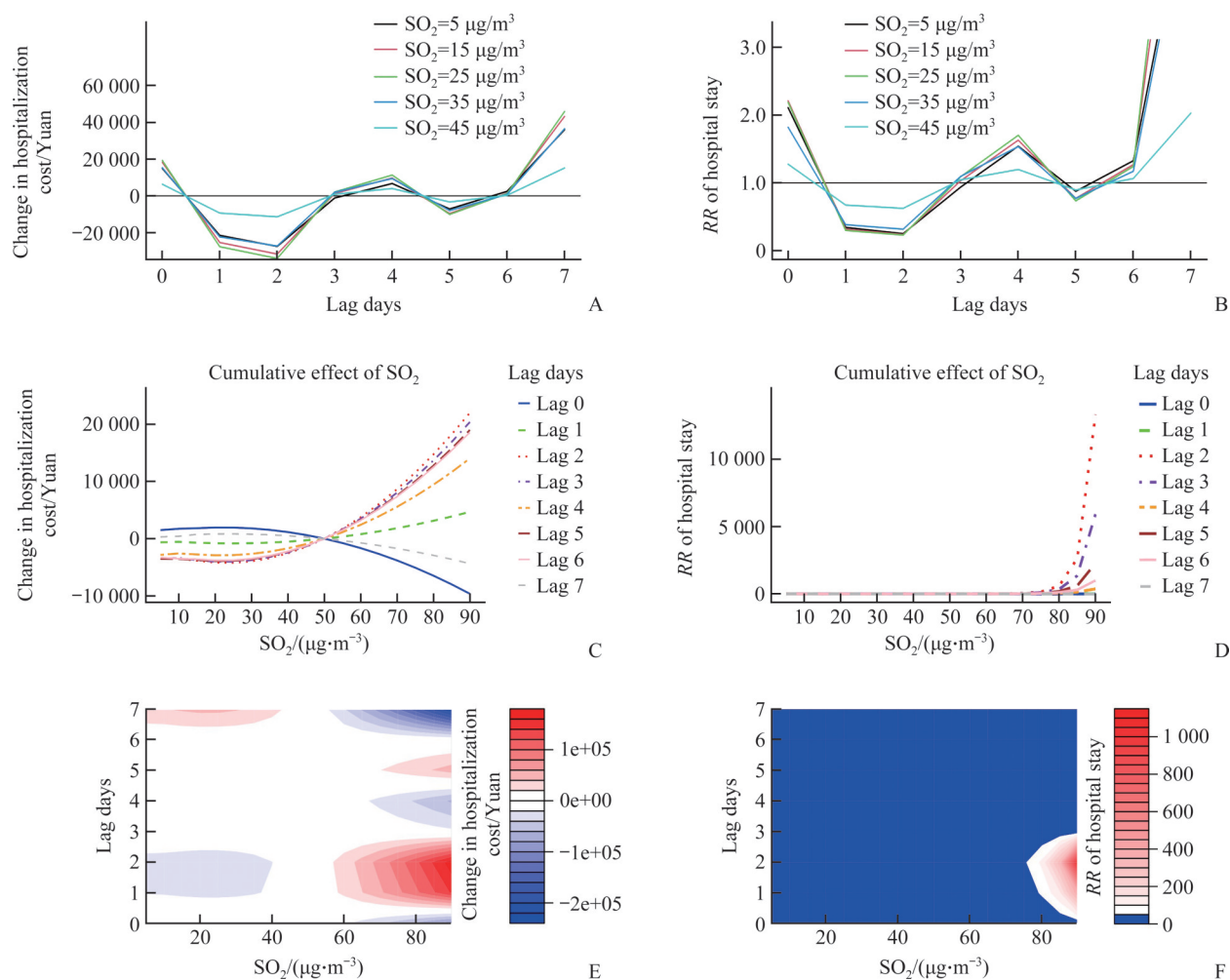


Figure 3 Associations between short-term SO_2 exposure and hospitalization outcomes among kidney transplant recipients with respiratory tract infections

A and B: Lag-response associations between SO_2 exposure at selected concentrations and changes in hospitalization cost (A) and the relative risk of prolonged hospital stay (B) for lag 0–7 days. C and D: Cumulative exposure-response curves showing the association between SO_2 concentration and changes in hospitalization cost (C) and the relative risk of prolonged hospital stay (D) for lag 0–7 days. E and F: Exposure-lag-response contour plots showing the association between SO_2 exposure and the relative risk of hospitalization cost across different lag periods (E) and the joint effects of SO_2 concentration and lag days on the relative risk of prolonged hospital stay (F). All models were adjusted for age, sex, body mass index, temperature, relative humidity, day of the week, and holidays.

3 Discussion

This study assessed the short-term impacts of air pollution on hospitalization burden—including both cost and length of stay—among kidney transplant recipients with respiratory tract infections. Our findings highlight that $\text{PM}_{2.5}$ and inhalable particles PM_{10} , as well as SO_2 , have measurable and often substantial associations with increased clinical and economic burden, particularly at higher concentrations and during cumulative exposures.

In contrast, CO , NO_2 , and O_3 showed minimal or inconsistent effects.

Among all pollutants, $\text{PM}_{2.5}$ had the most consistent and significant association with hospitalization outcomes. Exposure to elevated $\text{PM}_{2.5}$ levels—especially at or above $160 \mu\text{g}/\text{m}^3$ —was linked to marked increases in both cost and length of stay. The effects were most acute on the same day of exposure (lag day 0), suggesting an immediate clinical impact. While isolated lag effects beyond day 0 were modest, cumulative

exposures across lag days amplified the burden. These findings align with prior research showing that $PM_{2.5}$ penetrates deeply into the alveoli and exacerbates inflammation, posing a severe risk for immunocompromised individuals^[24]. Furthermore, $PM_{2.5}$ exposure is not uniform across vertical spaces. A recent study^[25] has shown that outdoor $PM_{2.5}$ concentrations peak around the 4th floor, then gradually decrease with increasing height, suggesting a vertical stratification likely influenced by traffic emissions and atmospheric mixing dynamics. For transplant recipients who spend extended time indoors, floor height may influence exposure risk, making it a meaningful factor in housing decisions.

Similarly, PM_{10} demonstrated a dose-dependent cumulative effect, particularly on hospital stay duration. Short-term associations at individual lags were less consistent, but prolonged hospitalization became evident at PM_{10} levels exceeding $150 \mu g/m^3$. This suggests a threshold phenomenon where risk escalates beyond regulatory limits. Given PM_{10} 's tendency to irritate airways and impair mucociliary function^[26], its impact may be magnified in post-transplant individuals with reduced respiratory defenses. Individual-level behaviors also interact with environmental conditions. Moderate physical activity has proven immune benefits for transplant recipients^[27], but the opportunity to exercise safely depends heavily on environmental infrastructure. Access to urban green spaces and walkable neighborhoods not only supports physical health but may also mitigate air pollution effects.

For SO_2 , our data showed relatively minor effects at concentrations under $50 \mu g/m^3$. However, when exposure exceeded $75 \mu g/m^3$, both hospitalization costs and duration rose significantly, especially under cumulative exposure. This aligns with SO_2 's biological potential to trigger inflammation and bronchospasm over time^[28]. Notably, in densely populated or industrial urban zones, SO_2 spikes may coincide with winter heating and poor ventilation—conditions under which respiratory infections are already more frequent, as reflected in our finding that most hospitalizations occurred in colder months.

In contrast, CO, NO_2 , and O_3 did not show

consistent or robust associations with hospitalization burden in this cohort. Though CO exposure above $2.0 mg/m^3$ showed a potential cost increase on early lag days, wide confidence intervals and inconsistent lag patterns suggest a limited role. O_3 and NO_2 exposures also varied by height and wind conditions, but their influence on outcomes here was minimal, possibly due to limited variation in individual exposure or differences in biological pathways.

From a practical standpoint, transplant recipients should adopt proactive strategies—particularly during winter and high-pollution periods. Avoiding crowded indoor spaces, firework-heavy holidays such as Lunar New Year, and exercising during low-pollution hours (such as late morning) are all advisable. Living on mid-level floors (such as 6th – 11th floors) may reduce exposure to both traffic-related PM and high-altitude ozone or inversion-trapped pollutants. Additionally, the use of air purifiers and fresh ventilation systems can dramatically lower indoor $PM_{2.5}$ levels, improving both comfort and clinical outcomes. Most importantly, patients and caregivers should be trained to recognize early symptoms of infection—fever, cough, and chest tightness—so that timely treatment can prevent clinical deterioration and reduce the burden of hospitalization.

Nevertheless, this study has several limitations. We were unable to account for indoor air quality, medication adherence, and social support, all of which can influence clinical outcomes. Future research should incorporate multi-pollutant models, account for regional infrastructure, and examine how chronic pollutant exposure affects long-term graft survival and quality of life.

Taken together, these results suggest that particulate pollution especially $PM_{2.5}$, PM_{10} and SO_2 poses the greatest short-term threat to post-transplant patients hospitalized with respiratory infections, with implications for both public health policy and clinical risk mitigation. Strategies targeting reductions in $PM_{2.5}$ and PM_{10} exposure—particularly during high-pollution periods—may help reduce healthcare utilization and costs in this high-risk group. Future studies should explore mechanistic links and assess whether pre-emptive interventions such as air filtration and early

outpatient monitoring during peak pollution days can mitigate adverse outcomes.

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