


Short-Term Associations Between Ambient Air Pollution and Outpatient and Emergency Visits for Hypertension: A DLNM-Based Time-Series Analysis in Baise, Guangxi, China

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Background: Despite growing evidence that short-term ambient air pollution increases hypertension risk, data from China's border regions are limited; this study quantifies the association between daily pollutant concentrations and daily emergency and outpatient visits for hypertension in Baise, a southern border city.

Methods: We collected hypertension case data from two tertiary hospitals in Baise City (1 Jan 2020–30 Dec 2022) and concurrent local air pollutant and meteorological data, and used a distributed lag non-linear model (DLNM) to assess pollutant effects on outpatient and emergency visits, with subgroup analyses by sex, age, and season.

Results: Every 10 $\mu\text{g}/\text{m}^3$ increase in $\text{PM}_{2.5}$ (lag06), PM_{10} (lag06), NO_2 (lag06), and every 100 $\mu\text{g}/\text{m}^3$ increase in CO (lag04), the risk of hypertension outpatient/emergency department visits increased by 3.2%, 2.8%, 14.8%, and 3.0%, respectively. Exposure–response curves were approximately linear without a clear threshold. There was no statistically significant effect modification by sex or age, whereas associations were stronger in the cold season than in the warm season.

Conclusion: Short-term exposure to pollutants such as $\text{PM}_{2.5}$, PM_{10} , NO_2 , and CO is significantly associated with increased outpatient and emergency visits for hypertension, exhibiting a lag effect. During cold seasons, sensitivity to environmental pollutants among hypertensive patients markedly increases.

Keywords: air pollutants, DLNM, relative risk, hypertension outpatient and emergency visits

Introduction

Hypertension (HTN), a significant worldwide health concern, is a principal contributor to the heightened illness load.¹ Relevant studies indicate that in 2023, there are more than 1.28 billion persons with hypertension globally, with 82% living in low and middle-income countries.² In the United States, the direct medical costs associated with hypertension amount to US\$1,497 per person per year, while in nations with poor and moderate incomes, this burden is even heavier.^{3,4} In China, about one-third of adults suffer from hypertension, and the prevalence increases significantly with age, exceeding 50% in the 70–74 age group.⁵ The Baise region, located on the southern border of China, faces a more prominent issue with the burden of hypertension due to the relatively lagging development of social health services.⁶

An increasing amount of epidemiological research has been done in recent years to examine the connection between air pollution and hypertension. Studies in the United Kingdom, Seoul in South Korea, Tehran in Iran, Guangzhou, and Shijiazhuang in China have shown a correlation between air pollutants and hypertension.^{7–11} However, most of these studies are concentrated in developed countries or central cities of developing countries, and the results often vary. These differences are related to the different mixtures of air pollutants and socio-demographic conditions in each city.¹² Similar research evidence is very limited in border cities of developing countries. Additionally, past studies have mainly used

generalized additive models to analyze the impact of real-time exposure levels on diseases, overlooking the delayed effects.

Baise City is situated in the western part of the Guangxi Zhuang Autonomous Region, at the southern border of China, where it lies at the intersection of two countries and three provinces (or regions). The city possesses a subtropical monsoon climate, distinguished by ample sunshine and warmth, including prolonged summers and brief winters. Covering a spatial extent of 36,300 km², Baise constitutes a prefecture-level city in southwestern China characterized by a predominantly Zhuang ethnic presence (accounting for over 80% of its population) and functioning as a strategic resource base for the national aluminum industry, with its industrial output contributing 12% to the country's total primary aluminum production. The city had 3.562 million permanent residents as of the end of 2022.¹³ Baise City's air quality ranks in the upper-middle tier among Chinese cities. Due to the unique geographical location, industrial structure, and social demographic conditions of Baise City, the results of other studies may not be applicable. This study employed a distributed lag non-linear model (DLNM) to investigate the short-term association between exposure to air pollutants and hypertension outpatient and emergency outpatient and emergency department visits in Baise City from 2020 to 2022. The primary objective is to systematically analyze the relationship between air pollutant levels and outpatient and emergency visits for hypertension. By meticulously examining the association between fluctuations in specific pollutant concentrations and patient visit frequency, the study aims to elucidate the impact of short-term air quality changes on hypertension outpatient and emergency visits. The findings will provide evidence-based support for developing targeted public health policies and interventions to reduce the societal burden of hypertension.

Materials and Methods

Air Pollution and Meteorological Information

Air pollution data for Baise City from January 1, 2020 to December 31, 2022 were obtained from the Statistics Center of the Department of Ecology and Environment of Guangxi Zhuang Autonomous Region (<http://sthjt.gxzf.gov.cn/>). The daily average concentrations of PM_{2.5}, PM₁₀, SO₂, NO₂, and CO, and the daily maximum 8-hour average ozone concentration (O₃8h) are the six major air pollutants examined in this study. All measurements adhere to the Chinese National Air Quality Control Standards (GB3095-2012). Daily meteorological data for the same time were also gathered from the China Meteorological Data Network (<http://data.cma.cn/>) for Baise City due to the possibility of nonlinear mixed effects from meteorological elements, as mentioned in other studies.^{14,15} Among the climatic factors examined and adjusted were the daily average temperature and relative humidity. All data collection activities were conducted simultaneously at 12 national meteorological stations and three national air quality monitoring stations. Site distribution is shown in [Figure S1](#). All three monitoring stations are located far from pollution sources, urban traffic, and buildings to ensure that the monitoring data accurately reflects the actual air pollution levels in our study area. Therefore, data obtained from these stations can represent the overall level of air pollution across the city. The missing rate for meteorological and atmospheric pollutant data is below 5%. Missing values are imputed using the average of the preceding and following dates.

Case Data Collection

Case data of hypertensive patients, including gender, age, visit date, and diagnosis codes, were collected from the Affiliated Hospital of Youjiang Medical University for Nationalities and the Southwest Hospital Affiliated to Youjiang Medical University for Nationalities during the study period. Both institutions rank among the largest and best-equipped comprehensive tertiary hospitals in Baise City. Together they operate three campuses, have a combined capacity exceeding 4,400 beds, and record over one million outpatient and emergency visits each year. The two hospitals have advanced and complete electronic medical record (EMR) systems. They are regional medical centers with patients from all districts and counties in Baise City. Cases with codes I10-I15 (hypertensive disorders) were included in this study, whereas non-permanent inhabitants of Baise City were excluded, following the International Classification of Diseases, 10th version (ICD-10) as the criterion for case selection. The dataset includes all outpatient and emergency visits recorded at the two hospitals.

Statistical Analysis

Spearman correlation analysis was conducted on daily hypertension outpatient and emergency visits about air pollutants and meteorological factors to identify and exclude those air pollutant factors not associated with hypertension outpatient and emergency visits. To prevent multicollinearity, when the absolute value of the correlation coefficient between two factors exceeded 0.7, these factors were not included simultaneously in the subsequent modeling.^{16,17} Considering the total population of Baise City, the daily hypertension outpatient and emergency visits of residents are a rare event, the data are highly dispersed, and the hypertension outpatient and emergency visits exhibit a nonlinear relationship with the concentration of air pollutants.¹⁸ Therefore, this study utilized the quasi-Poisson regression of the generalized additive model (GAM) combined with the DLNM.^{19,20}

The core idea of DLNM is to flexibly describe the nonlinear and lagged effects in the exposure-response relationship through cross-basis function (cross-basis) and, at the same time, to reduce the interference of confounding variables on causality estimation by incorporating them into the model as control variables, which is suitable for dealing with complex time series data.²⁰ In our study, we quantitatively assessed air pollutant-residential hypertension outpatient and emergency visits by using the environmental pollutant factors associated with the number of daily hypertension outpatient and emergency visits as the independent variables and the number of daily hypertension outpatient and emergency visits as the dependent variable, as well as controlling for the effects of confounding effects such as long-term trends in time, seasonality, and the influence of meteorological factors through the natural cubic spline (NS) function.^{21,22} The core model is as follows:^{23,24}

$$Y_t \sim \text{Quasipoisson}(\mu_t)$$

$$\text{Log}(\mu_t) = \alpha + \beta X_{t,L} + ns(\text{Tem}_t, df = 3) + ns(\text{rh}_t, df = 3) + ns(\text{Time}_t, df = 7 * 3) + \text{Dow} + \text{Hol}$$

Here, t denotes the date of a hypertension outpatient and emergency visits, L represents the lagged day count, β is the matrix coefficient, α indicates the intercept term, and $X_{t,L}$ is the cross-term basis function matrix for air pollutants. Y_t represents the number of hypertension outpatient and emergency visits on day t . The ns term represents the natural cubic spline function (ns). Tem_t and rh_t denote the temperature and relative humidity on day t , respectively. Time_t is the time variable. Dow (the value was 1 to 7) represents the sequence from Monday to Sunday, and Hol (categorical variable) is used to adjust for the day-of-week effect and holiday effect, respectively. Degrees of freedom were selected using the Quasi-Akaike information criterion (Q-AIC).²⁵ In this study, the degrees of freedom for the time variable were set to 7df/year to control for long-term and seasonal trends. The degrees of freedom for both mean temperature and relative humidity were set to 3 to account for the confounding effects of meteorological factors. Research indicates that the lagged effects of air pollutants on the cardiovascular system typically do not exceed 7 days.^{18,26} Consequently, the maximum lag duration in this study was set at seven days, and the model was fitted to investigate the impacts of cumulative multi-day delays (from lag01 to lag07) and single-day lags (from lag0 to lag7). After the model was constructed, the Relative Risk (RR) and 95% Confidence Interval (CI) of hypertension outpatient and emergency visits were calculated using the median concentration of ambient pollutants as the reference value for each 10 $\mu\text{g}/\text{m}^3$ increase in $\text{PM}_{2.5}$, PM_{10} , SO_2 , NO_2 , and O_3 8h (and each 100 $\mu\text{g}/\text{m}^3$ increase in CO).

Given the subtropical monsoon climate of the region, characterized by long, hot summers and short, mild winters, the annual temperature distribution in the study area actually exhibits a bimodal pattern. There is no continuous, distinct “hot” season that can be clearly distinguished from the broader “warm season.” During the warm season, temperatures remain consistently elevated, exerting a uniform influence on human behavior and physiological responses. Conversely, a distinct “cold season” is clearly delineated. This warm/cold dichotomy aligns with the region’s established climatic pattern. It represents a commonly employed methodology in regional epidemiological studies to control for the strong, differential confounding effects of temperature, particularly regarding cardiovascular health outcomes.^{27,28} The analysis was stratified by gender (male, female), age (<65 years, ≥ 65 years), and season (cold season: November to April of the following year, warm season: May to October), and intergroup differences were compared using the Z-test based on the analysis results to assess the susceptibility of different populations.²⁹ The formula for the Z-test is as follows:

$$Z = \frac{\beta_1 - \beta_2}{\sqrt{SE_{\beta_1}^2 + SE_{\beta_2}^2}}$$

Among them, β_1 and β_2 are the estimated effects for the two subgroups, SE_{β_1} and SE_{β_2} are the corresponding standard errors for the two subgroups. Finally, the stability of the model was tested using the dual-pollutant model and by altering the degrees of freedom in time.

IBM SPSS Statistics 26.0 software was used to characterize and analyze the data for Spearman correlation statistically; $P < 0.05$ was deemed statistically significant. The “dlnm” package in R software version 4.3.4 was used to fit the model.

Results

Basic Information

This research project encompassed 58,139 hypertensive patients ranging in age from 3 to 98 years old, with an average age of 51.1 years. On average, 53 patients visit the outpatient and emergency departments of the two hospitals each day. Male patients accounted for 54.31% of the total, while female patients constituted 45.69%. Patients under 65 years old comprised 53.45% of the cohort, with those aged 65 and above representing 46.55%. As shown in Table 1.

As shown in Table 2, AQI, PM_{2.5}, PM₁₀, SO₂, NO₂, CO, and O₃8h had average values of 48.04, 28.57 µg/m³, 49.30 µg/m³, 12.42 µg/m³, 16.63 µg/m³, 820.00 µg/m³, and 58.15 µg/m³, respectively. The average values for the climatic variables, temperature and relative humidity, were 20.51°C and 77.84%, respectively. During the 1,096 days covered by

Table 1 Daily Counts of Hypertension Outpatient and Emergency Visits in Baise, China, 2020–2022

Variables	Sum	Mean±SD	Min	P ₂₅	Median	P ₇₅	Max
Total	58139	53.05±22.83	1.00	40.00	56.50	69.00	121.00
Male	31578	28.81±12.27	1.00	22.00	31.00	37.00	65.00
Female	26561	24.23±11.77	0.00	17.00	25.00	33.00	60.00
<65 years	31077	28.35±12.34	0.00	22.00	30.00	37.00	60.00
≥65 years	27062	24.69±11.92	0.00	17.00	26.00	33.00	66.00
Warm season	28065	50.84±19.89	3.00	40.00	54.00	65.00	99.00
Cold season	30074	55.28±25.30	1.00	40.25	60.00	74.00	121.00

Notes: Statistics include mean, Cumulative Sum (Sum), standard deviation (SD), minimum (Min), 25th Percentile (P₂₅), 75th Percentile (P₇₅) and maximum (Max) values.

Table 2 Summary Statistics of Daily Air Pollutant Concentrations and Meteorological Variables in Baise, China, 2020–2022

Variables	Mean±SD	Min	P ₂₅	Median	P ₇₅	Max
AQI	48.04±19.32	15.00	35.00	45.00	57.00	174.00
PM _{2.5} (µg/m ³)	28.57±16.77	1.00	17.00	24.00	37.00	132.00
PM ₁₀ (µg/m ³)	49.30±23.64	6.00	33.00	44.00	61.75	189.00
SO ₂ (µg/m ³)	12.42±5.01	4.00	8.00	12.00	16.00	30.00
NO ₂ (µg/m ³)	16.63±6.70	6.00	12.00	15.00	19.75	66.00
CO (µg/m ³)	820.00±160.00	230.00	730.00	800.00	900.00	1800.00
O ₃ 8h (µg/m ³)	58.15±24.62	6.00	40.00	57.00	75.00	145.00
Mean temperature (°C)	20.51±6.11	4.60	15.83	21.40	26.00	30.60
Relative humidity (%)	77.84±8.86	39.00	73.00	78.00	84.00	97.00

Notes: AQI, Air Quality Index. Pollutant concentrations are given in micrograms per cubic meter (µg/m³). Meteorological variables: Mean temperature is measured in °C; relative humidity is measured in %. Statistics include mean, Cumulative Sum (Sum), standard deviation (SD), minimum (Min), 25th Percentile (P₂₅), 75th Percentile (P₇₅) and maximum (Max) values.

this study, a total of 468 days failed to meet air quality standards based on the Air Quality Index (AQI) criteria (defined as days with AQI > 50), accounting for 42.7% of the total days.

The time series for daily total hypertension outpatient and emergency visits and airborne pollutants levels during the course of the investigation are shown in [Figure 1](#). There are noticeable seasonal variations in the concentrations of PM_{2.5}, PM₁₀, NO₂, and CO, which are lower in summertime and fall and higher in the winter and spring. In contrast, the levels of O₃8h show an inverse pattern, with higher concentrations in the warmer months. SO₂, however, does not demonstrate a distinct seasonal trend.

Analysis of the Correlation Between Hypertension Outpatient and Emergency Visits and Air Pollutants, Meteorological Factors

[Table 3](#) displays the correlation between hypertension outpatient and emergency visits and both air pollutants and meteorological factors. Notably, the correlations between SO₂ and O₃8h with hypertension outpatient and emergency visits were not statistically significant ($P > 0.05$). As a result, only PM_{2.5}, PM₁₀, NO₂, and CO were considered as exposure factors for air pollutants. PM_{2.5}, PM₁₀, and NO₂ show strong correlations with each other ($|r| > 0.7$), so any two of these factors were not included in the model simultaneously.

The Impact of Short-Term Exposure to Air Pollutants on Hypertension Outpatient and Emergency Visits

Exposure-Response Curves

The exposure-response curves between hypertension outpatient and emergency visits at lag07 and air pollution are shown in [Figure 2](#). The curves for PM_{2.5}, PM₁₀, NO₂, and CO exhibit nearly linear relationships, with no evident threshold for the relative risk of hypertension outpatient and emergency visits. As the concentrations of these pollutants rise, the cumulative relative risk increases correspondingly.

The Impact and Lag (Cumulative) Effects of Different Air Pollutants

[Table 4](#) shows the RR and 95% CI for the number of hypertension outpatient and emergency visits at different lag times for every 10 µg/m³ rise in the concentration of air pollutants (and for every 100 µg/m³ increase in CO concentration). PM_{2.5} has an adverse effect on hypertension outpatient and emergency visits from lag01 to lag07 days. Among these, the most significant impact was observed on lag 06, with an RR value of 1.032 (95% CI: 1.015, 1.048). PM₁₀ had adverse effects on lag0, lag1, lag4, lag5, and lag01 to lag07 days, with the most significant impact on lag06 days, with an RR value of 1.028 (95% CI: 1.016, 1.039). NO₂ showed adverse effects on lag0, lag1, lag4, and from lag01 to lag07 days, with the most significant impact occurring on lag06, where the RR value was 1.148 (95% CI: 1.104, 1.194). CO had an adverse effect on lag1, lag2, and from lag01 to lag06 days, with the most significant impact observed on lag04, with an RR value of 1.030 (95% CI: 1.016, 1.045).

The Impact of Air Pollutants on Hypertension Outpatient and Emergency Visits in Different Subgroups of the Population

Gender Subgroup

[Figure 3](#) and [Table S1](#) show the relative risk (RR) and 95% confidence interval (CI) for the number of hypertension-related emergency and outpatient visits across different genders in the single-pollutant model. The findings show that although there are slight differences in the relative risk of hypertension for the two subgroups exposed to the four air pollutants, these differences are not statistically significant ($P > 0.05$).

Age Subgroup

[Figure 4](#) and [Table S2](#) show the relative risk (RR) and 95% confidence interval (CI) for the number of hypertension emergency and outpatient visits across different age groups in the single-pollutant model. Four air pollutants, PM_{2.5}, PM₁₀, NO₂, and CO, have adverse effects on hypertension across different age groups, but the differences in these adverse effects between the two subgroups are not statistically significant ($P > 0.05$).

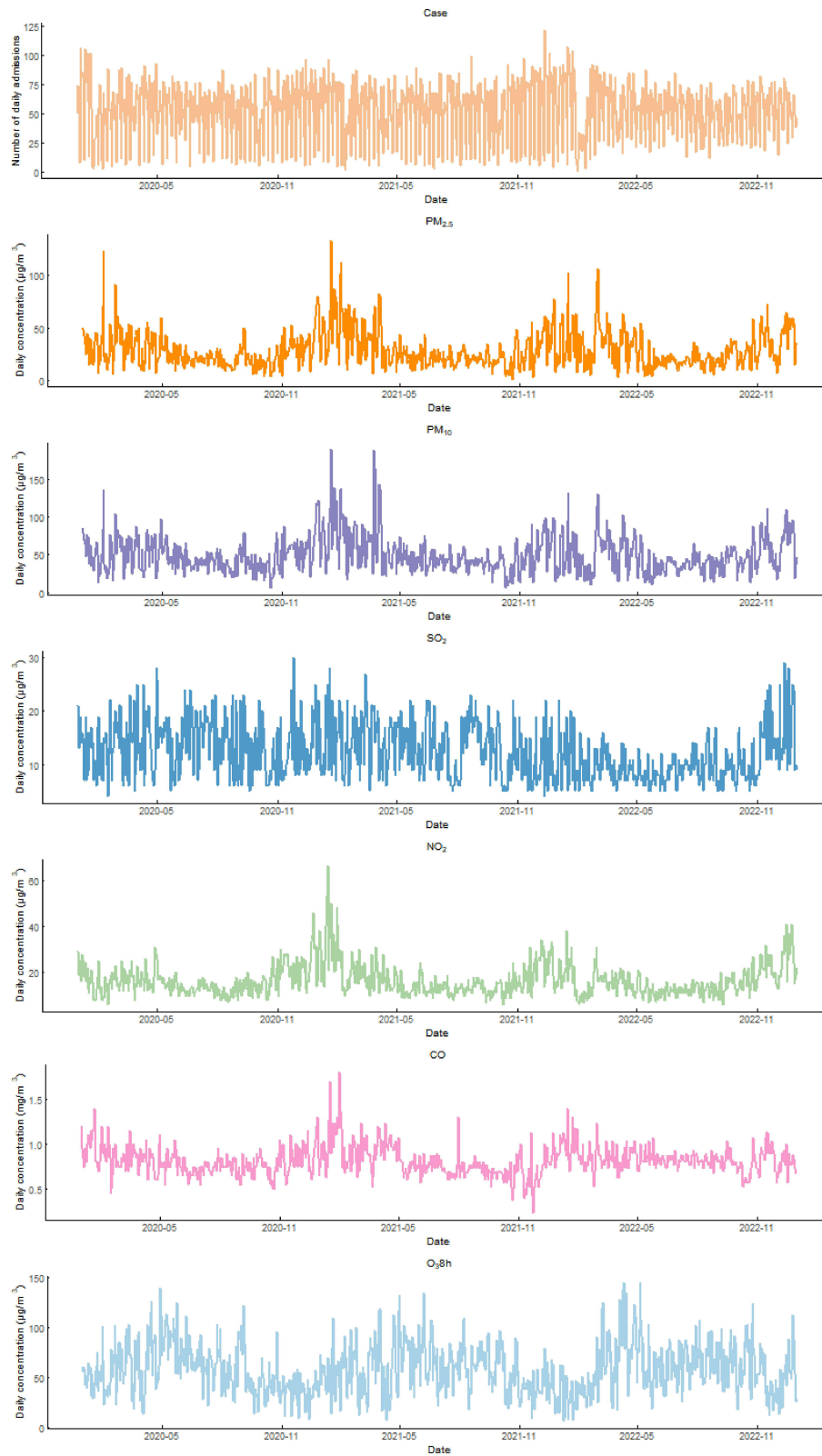


Figure 1 Time series of hypertension outpatient and emergency visits and air pollution concentrations in Baise, China, 2020–2022.

Table 3 Spearman Rank Correlations Among Daily Hypertension Visits, Air Pollutant Concentrations, and Meteorological Variables in Baise, 2020–2022

Variables	Case	PM _{2.5}	PM ₁₀	SO ₂	NO ₂	CO	O ₃ 8h	Mean Temperature	Relative Humidity
Case	1								
PM _{2.5}	0.113**	1							
PM ₁₀	0.123**	0.949**	1						
SO ₂	0.015	0.472**	0.537**	1					
NO ₂	0.180**	0.716**	0.742**	0.393**	1				
CO	0.068*	0.467**	0.432**	0.313**	0.397**	1			
O ₃ 8h	0.013	0.279**	0.367**	0.269**	-0.015	-0.05	1		
Mean temperature	-0.097**	-0.186**	-0.054	0.196**	-0.364**	-0.170**	0.501**	1	
Relative humidity	-0.046	-0.317**	-0.400**	-0.158**	-0.227**	0.207**	-0.620**	-0.172**	1

Notes: *P < 0.05, **P < 0.01.

Seasonal Subgroup

Figure 5 and Table S3 show the relative risk (RR) and 95% confidence interval (CI) for the number of hypertension-related emergency and outpatient visits across different seasons in the single-pollutant model. Research findings indicate that air pollution exhibits significant seasonal variation in its impact on hypertension outpatient and emergency visits ($P < 0.05$). In particular, during the cold season, as opposed to the warm season, the effects of PM_{2.5}, PM₁₀, NO₂, and CO on

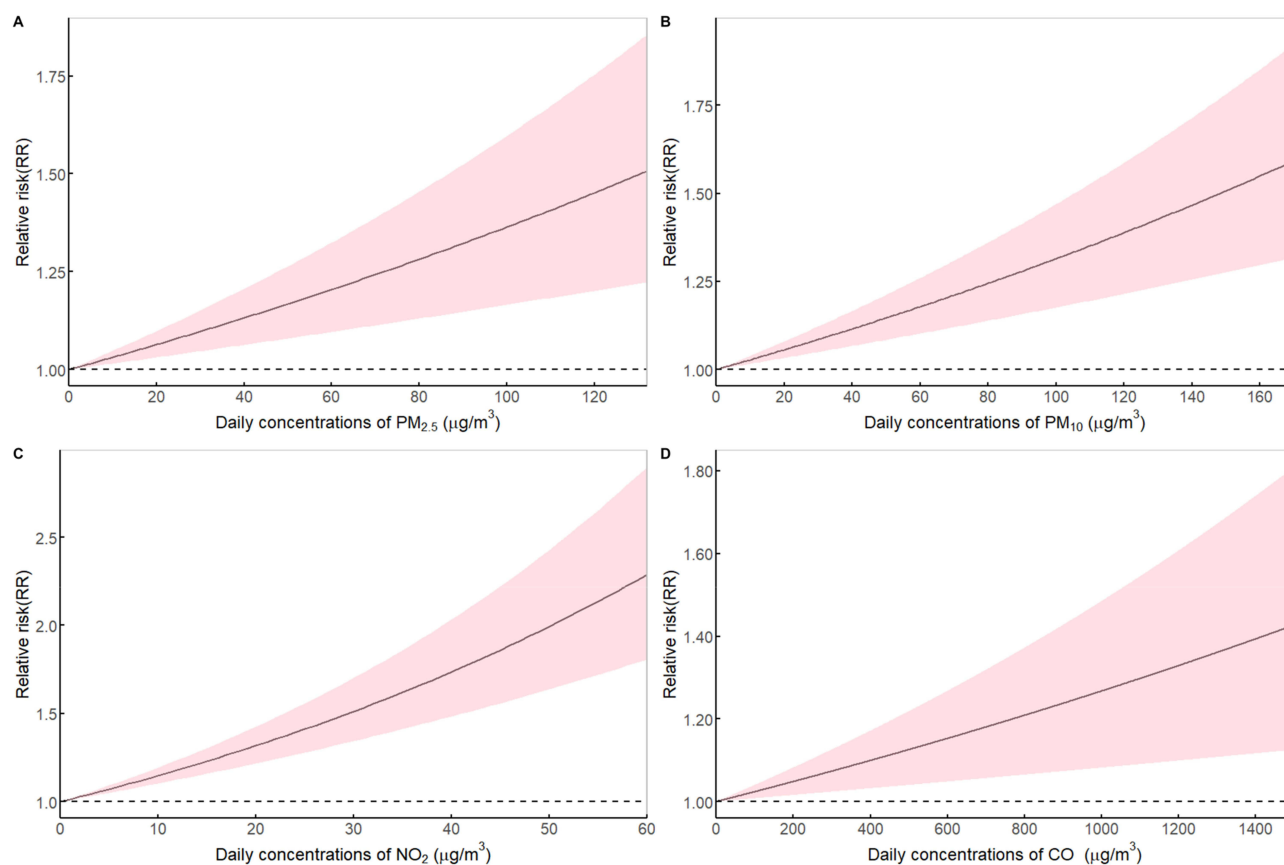


Figure 2 The air pollution exposure-response curves with hypertension outpatient and emergency visits at lag7. (A) PM_{2.5}, (B) PM₁₀, (C) NO₂, (D) CO.

Table 4 Relative Risk (95% Confidence Interval) of Hypertension Outpatient and Emergency Visits Associated with a 10 µg/m³ Rise in Air Pollutants (and 100 µg/m³ in Carbon Monoxide) as per the Single-Pollutant Model

Lag Days	PM _{2.5}	PM ₁₀	NO ₂	CO
lag0	1.010(0.999,1.020)	1.010(1.003,1.018)*	1.055(1.025,1.087)*	1.014(1.003,1.026)*
lag1	1.004(0.999,1.009)	1.004(1.001,1.007)*	1.025(1.011,1.039)*	1.007(1.002,1.012)*
lag2	1.003(0.997,1.009)	1.001(0.997,1.005)	1.013(0.995,1.030)	1.004(0.997,1.010)
lag3	1.003(0.999,1.008)	1.002(0.999,1.005)	1.011(0.998,1.025)	1.003(0.998,1.008)
lag4	1.005(0.999,1.009)	1.004(1.001,1.007)*	1.014(1.001,1.028)*	1.002(0.997,1.007)
lag5	1.005(0.999,1.011)	1.004(1.001,1.009)*	1.015(0.997,1.032)	0.999(0.993,1.006)
lag6	1.002(0.997,1.007)	1.002(0.999,1.006)	1.007(0.993,1.021)	0.994(0.989,0.999)*
lag7	0.995(0.985,1.006)	0.996(0.989,1.003)	0.985(0.956,1.014)	0.984(0.973,0.995)*
lag01	1.014(1.002,1.026)*	1.014(1.006,1.022)*	1.082(1.048,1.117)*	1.021(1.008,1.035)*
lag02	1.017(1.005,1.029)*	1.015(1.007,1.024)*	1.096(1.060,1.132)*	1.025(1.011,1.039)*
lag03	1.020(1.007,1.033)*	1.017(1.008,1.026)*	1.108(1.070,1.147)*	1.028(1.014,1.043)*
lag04	1.025(1.011,1.038)*	1.021(1.012,1.030)*	1.123(1.085,1.163)*	1.030(1.016,1.045)*
lag05	1.029(1.015,1.045)*	1.025(1.015,1.036)*	1.140(1.098,1.184)*	1.030(1.014,1.046)*
lag06	1.032(1.015,1.048)*	1.028(1.016,1.039)*	1.148(1.104,1.194)*	1.024(1.008,1.040)*
lag07	1.027(1.011,1.043)*	1.024(1.013,1.035)*	1.130(1.092,1.170)*	1.008(0.994,1.022)

Notes: Bold indicates statistically significant results (*P < 0.05).

HTN are more noticeable. The most significant adverse impacts are reported at lag 06 for PM_{2.5}, PM₁₀, and CO, and at lag05 for NO₂, with corresponding relative risk (RR) values of 1.038 (95% CI: 1.017, 1.060), 1.034 (95% CI: 1.019, 1.050), 1.176 (95% CI: 1.120, 1.234), and 1.041 (95% CI: 1.021, 1.061).

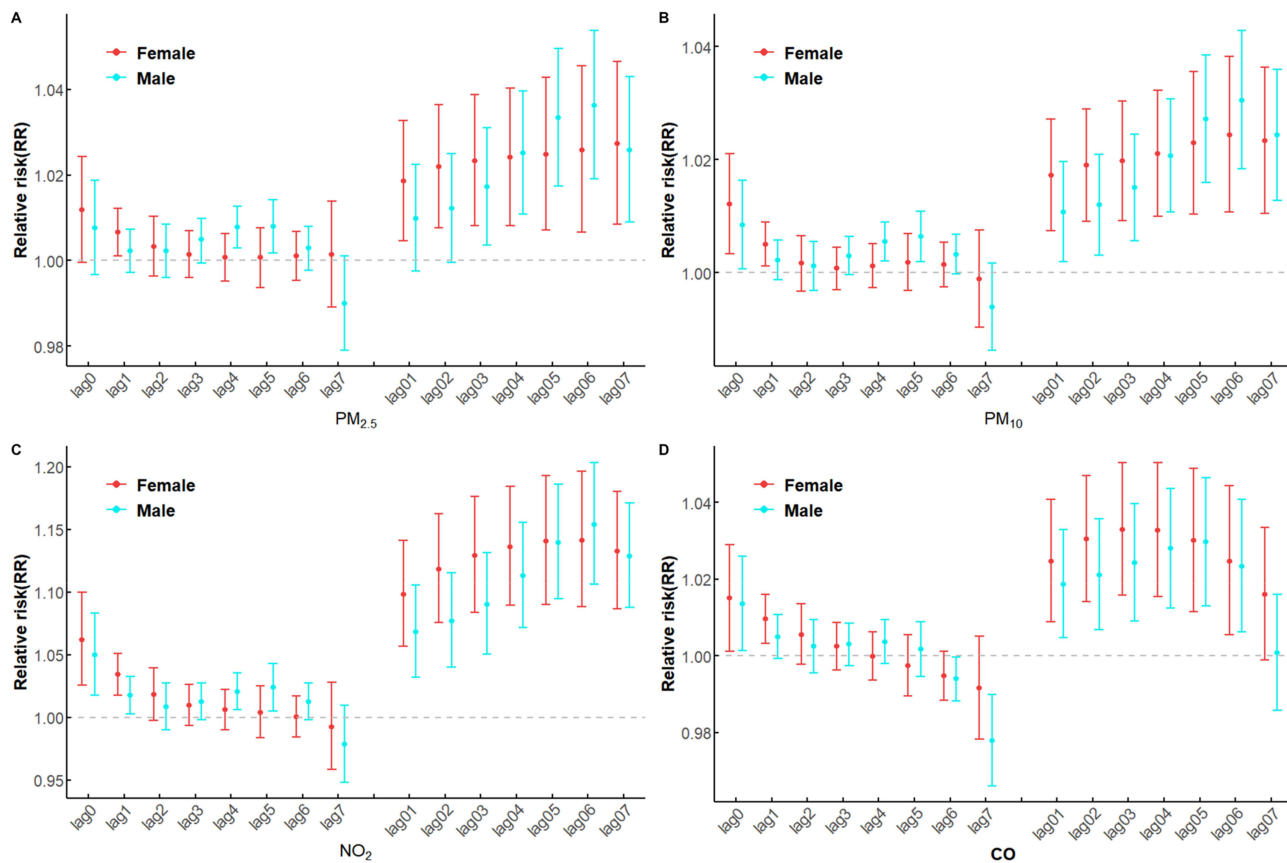


Figure 3 Relative risk (95% CI) of hypertension outpatient and emergency visits stratified by sex for each 10 µg/m³ increase in air pollutant concentration (each 100 µg/m³ increase in CO) in single-day lags and cumulative lags. (A) PM_{2.5}, (B) PM₁₀, (C) NO₂, (D) CO.

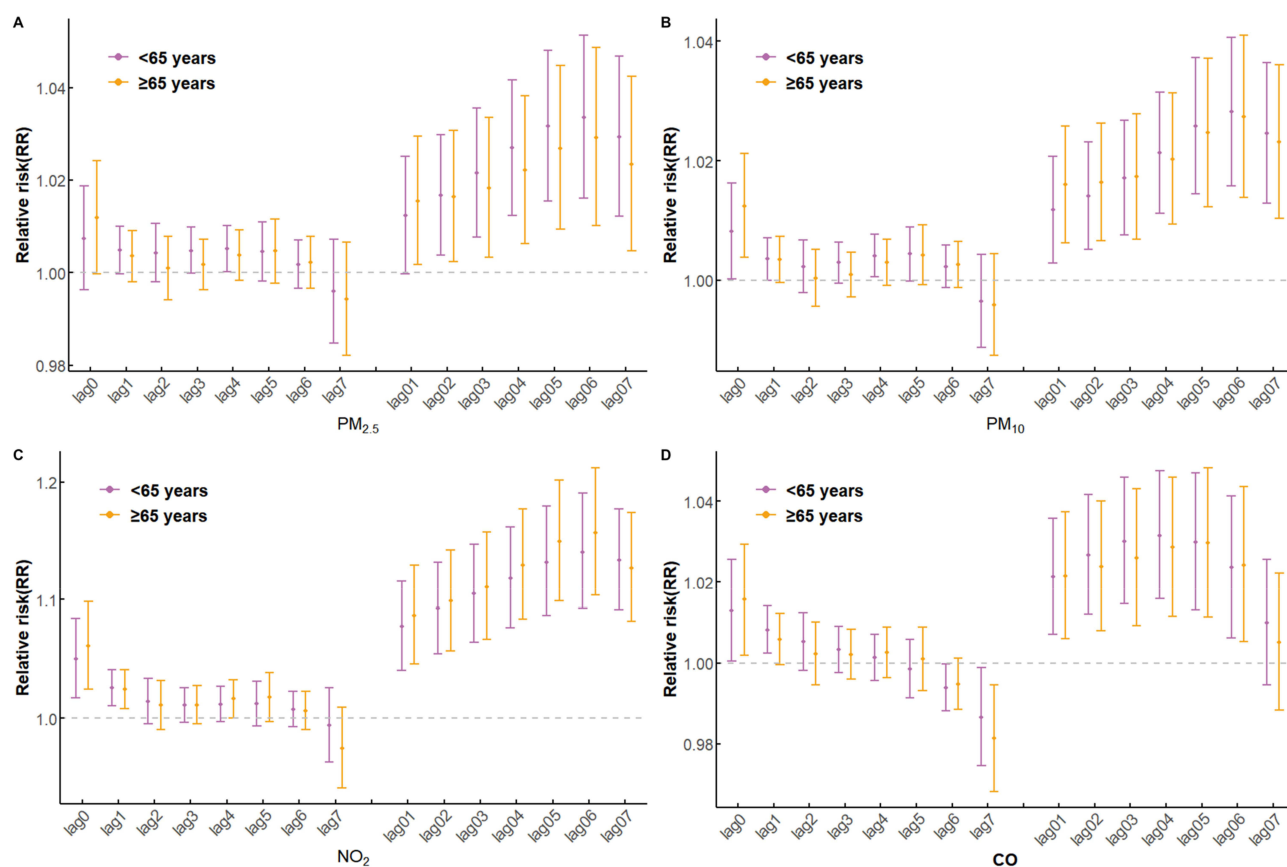


Figure 4 Relative risk (95% CI) of hypertension outpatient and emergency visits stratified by age for each $10 \mu\text{g}/\text{m}^3$ increase in air pollutant concentration (each $100 \mu\text{g}/\text{m}^3$ increase in CO) in single-day lags and cumulative lags. **(A)** $\text{PM}_{2.5}$, **(B)** PM_{10} , **(C)** NO_2 , **(D)** CO.

Model Sensitivity Analysis

[Table S4](#) presents the results showing changes in the relative risk (RR) values for hypertension outpatient and emergency visits corresponding to a $10 \mu\text{g}/\text{m}^3$ increase in $\text{PM}_{2.5}$, PM_{10} , and NO_2 concentrations (as well as a $100 \mu\text{g}/\text{m}^3$ increase in CO concentration) calculated using both single-pollutant and dual-pollutant models. Due to the strong correlation between $\text{PM}_{2.5}$, PM_{10} , and NO_2 , $\text{PM}_{2.5}$, PM_{10} , and NO_2 will not coexist simultaneously in the model, with only two of them present at a time. After incorporating other pollutants into the model, all pollutants maintained a significantly stable association with the relative risk of hypertension outpatient and emergency visits at lag07 days. [Table S5](#) shows the results of evaluating the model's robustness by changing the time freedom from 6 to 10, with no significant change in the effect estimates. The above results indicate that the relationship between air pollution derived from the model and the hypertension outpatient and emergency visits is stable and reliable, with a good model fit.

Discussion

This study covers 58,139 cases of hypertension treated in two hospitals in Baise City from January 2020 to December 2022. The study findings suggest that short-term exposure to $\text{PM}_{2.5}$, PM_{10} , NO_2 , and CO is significantly associated with visits to outpatient clinics and emergency departments for hypertension. The relationship between air pollutants and the number of hypertension outpatient and emergency visits varies by season, with no statistically significant differences between genders or age groups. Since this study is a retrospective ecological study, this implies that such associations do not constitute strong causal relationships.

Research has found that increases in environmental concentrations of $\text{PM}_{2.5}$, PM_{10} , NO_2 , and CO are all associated to varying degrees with rising numbers of outpatient and emergency visits for hypertension. The outcomes of this study are generally comparable to those of other cities, but there are differences in the extent of the impact. For example, a study

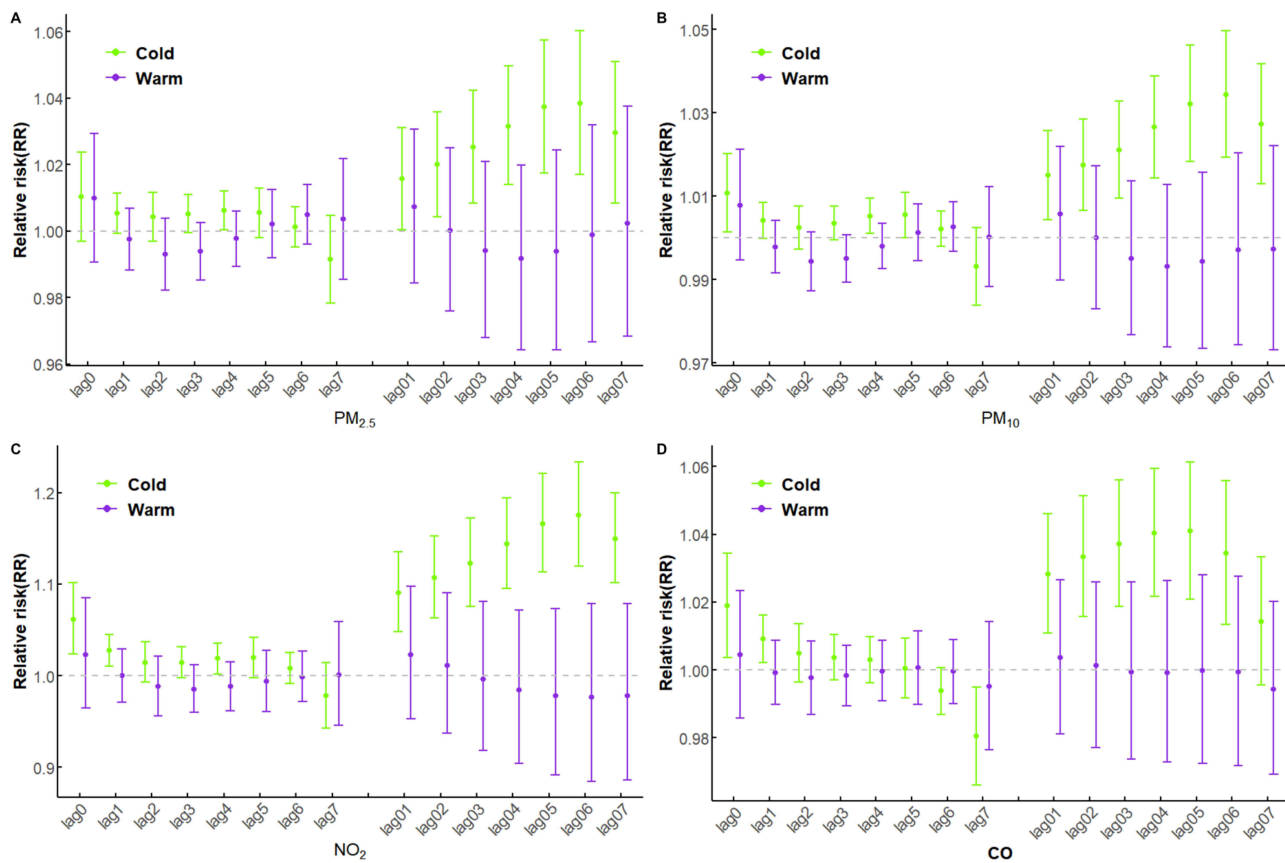


Figure 5 Relative risk (95% CI) of hypertension outpatient and emergency visits stratified by season for each $10 \mu\text{g}/\text{m}^3$ increase in air pollutant concentration (each $100 \mu\text{g}/\text{m}^3$ increase in CO) in single-day lags and cumulative lags. (A) $\text{PM}_{2.5}$, (B) PM_{10} , (C) NO_2 , (D) CO.

from Fuzhou, China, showed that for every $10 \mu\text{g}/\text{m}^3$ increase in the concentrations of $\text{PM}_{2.5}$, PM_{10} , NO_2 , and CO, the hospital admission rates for individuals with HTN increased by 0.56%, 0.31%, 1.18%, and 0.03%, respectively.³⁰ A research report from Isfahan, Iran, indicates that for every $10 \mu\text{g}/\text{m}^3$ increase in PM_{10} concentration, the risk of hospital admissions related to HTN increases significantly by 2.11%.³¹ A study in Ahvaz, Iran, indicates that for every $10 \mu\text{g}/\text{m}^3$ increase in NO_2 concentration, the risk of hospital admission for HTN increases by a ratio of 1.026 (95% CI: 1.007, 1.045).²⁶ These differences in the extent of the impact may be related to Baise City's location on the southwestern border, its unique social demographic conditions, and varying levels of air pollution, or it could be due to Baise City's relatively lower socioeconomic status and average education level compared to inland central cities, resulting in lower living standards and health literacy.^{32,33} Therefore, further discussion is needed on research related to similar border cities.

In terms of lag effects, this study found that the adverse effects of $\text{PM}_{2.5}$, PM_{10} , and NO_2 were strongest at lag06 days, while the lag effect of CO was strongest at lag04 days. This differs from previous research findings. Song et al discovered in Shijiazhuang that the effects of $\text{PM}_{2.5}$, PM_{10} , NO_2 , and CO were most significant at lag06, lag06, lag03, and lag04, respectively.¹¹ Liu et al, in their study in Lanzhou, found that the adverse effects of $\text{PM}_{2.5}$ and PM_{10} were most significant at lag07. At the same time, those of NO_2 and CO were most significant at lag1.¹⁸ The reason for this disparity may be that the majority of residents in Baise City are ethnic minorities. Different populations have varying susceptibilities to diseases.³⁴ The differences in the sources and composition of pollutants may also play a role. For instance, in Lanzhou, particulate matter (PM) primarily comprises mixed pollution from traffic and coal combustion, including fat-soluble substances such as Polycyclic Aromatic Hydrocarbons (PAHs). These components remain in the alveoli for extended periods, resulting in prolonged metabolic clearance and a longer timeframe required to accumulate

their toxic effects.³⁵ In contrast, Baise contains industrial aluminum dust (eg, fluoride), which has high solubility and may reduce the lung retention time, potentially accelerating the peak of cumulative toxicity compared to Lanzhou.³⁶

Exposure-response curves play a vital role in assessing the impact of environmental factors on non-communicable diseases. This study identified an approximately linear relationship between the concentrations of PM_{2.5}, PM₁₀, NO₂, and CO and the relative risk of hypertension outpatient and emergency visits. However, limited literature examines the exposure-response relationship between air pollutants and HTN. For instance, in a previous study conducted in Lanzhou, the exposure-response curves for NO₂ and CO were relatively stable compared to the findings in this study.¹⁸ This may be because the high exposure in Lanzhou City leads to adaptive responses in the body, which weaken the effect of pollutants per unit concentration increment and manifests itself as a flattening of the curve; at the same time, Baise City is located in a border area with a high percentage of ethnic minorities among the inhabitants, and the genetic factors and the low availability of healthcare resources may exacerbate the effects of pollution exposure.³⁷

Identifying potentially susceptible subgroups holds significant implications for public health. After stratification by gender and age, this study found no significant differences in the association between PM_{2.5}, PM₁₀, NO₂, and CO across the two groups. These results differ from some previous studies. For example, the Lanzhou study found that PM_{2.5} and PM₁₀ had a greater impact on hypertension in women than in men, while NO₂ and CO had a more significant effect on men. Additionally, individuals aged ≥ 65 years exhibited heightened sensitivity to the adverse effects of PM_{2.5}, PM₁₀, SO₂, and CO.¹⁸ A Fuzhou study indicated more substantial impacts of PM_{2.5} and PM₁₀ on males,³⁰ but the Yichang study found no evidence of gender playing a role in the relationship between ambient air pollution and cardiovascular disease.³⁸ These differences may relate to regional variations in lifestyle factors such as dietary habits and outdoor activity duration.^{39,40} Additionally, the effects of air pollutants on the cardiovascular system often operate through common pathways like inflammation and oxidative stress. Biological responses to these mechanisms may be similar across different demographic groups, potentially explaining the lack of significant effect differences.⁴¹

The seasonal stratification analysis showed that the impact of PM_{2.5}, PM₁₀, NO₂, and CO on hypertension outpatient and emergency visits was more substantial during the cold season, with all differences being statistically significant. This is similar to the findings of a study in Shenzhen.⁴² The proportion of polycyclic aromatic hydrocarbons (PAHs) and heavy metals in PM produced by residential coal combustion is elevated in the cold season, and these components can exacerbate vascular endothelial damage by inducing oxidative stress and inflammatory responses;³⁵ at the same time, it has been shown in a study that an increase in outdoor recreational activities reduces the level of patient's BP, and that residents' outdoor activities are significantly lower in the cold season compared to the warm season, which may also contribute to the existence of hypertension outpatient and emergency visits seasonal differences in hospital may also be one of the reasons.⁴³

Hypertension is a chronic disease caused by the combined effects of multiple factors, primarily influenced by genetics, environment, diet, and other factors. Its pathogenesis involves multiple pathways. However, existing research indicates that air pollutants primarily affect blood pressure through four pathways. First, environmental pollutants stimulate inflammatory responses and oxidative stress within the body, leading to vascular endothelial dysfunction and elevated blood pressure;^{44,45} second, pollutants can enter the bloodstream, impairing vasodilation function and thereby increasing blood pressure;⁴⁶ Third, pollutants stimulate the sympathetic nervous system, simultaneously affecting blood pressure and activating the hypothalamic-pituitary-adrenal axis, thereby elevating blood pressure through sodium and water retention and vasoconstriction mechanisms;^{47,48} Fourth, certain trace elements in environmental pollutants can regulate blood pressure by rapidly inducing hypomethylation of specific genes.⁴⁹ Due to variations in the subcomponents of environmental pollutants and trace element concentrations across different regions, this may explain the discrepancies observed in epidemiological evidence regarding the impact of air pollutants on hypertension across different areas.

Industrial emissions significantly increase the burden of cardiovascular disease. A study from Yichang provides empirical evidence by comparing cardiovascular disease (CVD) outpatient visits before and after industrial relocation along the Yangtze River: relocating heavily polluting industries away from the river improved local air quality. It significantly reduced CVD outpatient demand, demonstrating that strict industrial relocation policies along the river can simultaneously achieve environmental improvements and cardiovascular health benefits.³⁸ Given the documented improvements in air quality and cardiovascular health following the relocation of heavy industries along the Yangtze

River in Yichang, similar policy approaches could be considered for the aluminum industry layout in Baise City. For instance, high-emission aluminum plants could be gradually relocated to areas with lower river density and reduced exposure risks for residents. Concurrently, measures such as installing industrial air-filtration systems and implementing process improvements to curb emissions could be adopted to mitigate pollution and alleviate the health burden on surrounding communities.

This study also has limitations. First, similar to most previous studies, it used average concentrations measured at fixed monitoring stations as indicators of personal exposure levels. Due to the spatial variability of air pollutants, this approach may introduce bias into exposure assessment results.⁵⁰ Second, the inclusion of data from only one city, Baise, limits the extrapolation of conclusions. Third, it should be noted that although the overall sample size is adequate, the reduction in sample size after stratification may decrease the power of the study. Fourth, the time series includes the COVID-19 pandemic period. Although we have made every effort to control for long-term and seasonal variations in the data and ensure model robustness, this may still lead to underestimated effects in the results. Caution should be exercised when extrapolating findings. However, this study captures the temporary shifts in healthcare-seeking behavior during a significant public health crisis. It provides valuable real-time evidence for post-pandemic healthcare resource forecasting and planning, with conclusions that hold greater practical significance than simple extrapolations based on historical data.

In the future, we will integrate personal exposure monitoring technologies to reduce measurement errors and assess individual heterogeneity in exposure-dose relationships. Simultaneously, we will conduct comparative studies across multiple cities or regions, incorporating diverse pollution characteristics to enhance the generalizability of findings. Furthermore, we will introduce mechanistic research measures—through biomarker detection or combined with ambulatory blood pressure monitoring—to investigate the physiological pathways by which short-term pollution exposure affects blood pressure. This will strengthen causal associations and improve intervention feasibility.

Conclusion

The present study shows that short-term increases in ambient PM_{2.5}, PM₁₀, NO₂, and CO are positively associated with higher rates of hypertension-related visits. The most significant effects were observed at lag06 for PM_{2.5}, lag06 for PM₁₀, lag04 for NO₂, and lag06 for CO. Subgroup analyses indicated that these associations were significantly stronger during the cold season than the warm season, while no statistically significant differences were found by age or sex. These findings underscore the importance of timely air-quality monitoring and public health advisories—particularly in cold months to reduce acute hypertension risk through individual protective measures and targeted interventions. Overall, this study adds evidence linking short-term ambient air pollution to hypertension morbidity in a developing border city and highlights implications for environmental health policy; further research is warranted to clarify causal mechanisms and to evaluate the effectiveness of mitigation strategies.

Abbreviations

PM_{2.5}, particulate matter <2.5 μm in aerodynamic diameter; PM₁₀, particulate matter <10 μm in aerodynamic diameter; SO₂, sulfur dioxide; NO₂, nitrogen dioxide; CO, carbon oxide; O₃8h, daily 8-hour mean concentrations of ozone; AQI, Air Quality Index; HTN, hypertension; GAM, generalized additive model; DLNM, distributed lag non-linear models; RR, relative risk; CI, confidence interval; Q-AIC, Quasi-Akaike information criterion.

Data Sharing Statement

The datasets generated and/or analyzed during the current study are not publicly available but can be obtained from the corresponding author upon reasonable request.

Institutional Review Board Statement

The Youjiang Medical University for Nationalities Medical Ethics Committee approved the study protocol (Approval No. 2023120401). This study was conducted in accordance with the Declaration of Helsinki.

Informed Consent Statement

Since this study is a retrospective ecological study using aggregated data and does not involve personal privacy, the requirement for informed consent was waived with the approval of the Medical Ethics Committee of Youjiang Medical University for Nationalities.

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Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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Disclosure

The authors declare that they have no competing interests in this work.

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