

Focusing on an understudied population: Short-term air pollution exposure and metabolic syndrome indicators among rural adults in Central China

Zhuolin Shi

the First Affiliated Hospital of Henan Medical University

Jing You

Henan Medical University

Yuhan Li

Henan Medical University

Zhen An

Henan Medical University

Huijun Li

Henan Medical University

Jie Song

Henan Medical University

Guofu Zhang

Henan Medical University

Weidong Wu

Henan Medical University

Hui Wu

wuhui@hamu.edu.cn

Henan Medical University

Short Report

Keywords: MetS, Morbidity, Atmospheric particulate matter, Short-term effects

Posted Date: September 24th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10839993/v1>

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Additional Declarations: No competing interests reported.

Abstract

Background

MetS is a high-risk factor for chronic diseases; air pollution may affect its components. Few studies examined short-term exposure and metabolic indicators in rural populations. We evaluated MetS occurrence and the association between short-term particulate matter exposure and MetS components in rural central China.

Methods

This prospective cohort used 2017 baseline and 2021 follow-up data. Daily concentrations of PM_{2.5}, PM₁₀, NO₂, SO₂, CO, O₃ (May 19–Jul 20, 2021) were obtained. Generalized linear models evaluated lag (0–7) and cumulative lag (01–07) effects on SBP, DBP, TG, HDL-C, FBG. Sensitivity analysis used four MetS criteria. Results: 4-year cumulative incidence 16%, age-standardized 12.64%. Associations were weak. In cumulative lag models, PM₁₀ and SO₂ associated with increased SBP; PM_{2.5}, PM₁₀, SO₂ with increased DBP; SO₂, CO, O₃ with decreased HDL-C; NO₂ with increased FBG.

Conclusions

Short-term air pollution exposure weakly correlated with MetS components; cumulative exposure had stronger effects on blood pressure and fasting glucose than single-day exposure.

Background

Metabolic syndrome (MetS) is a cluster of obesity, hyperglycaemia, dyslipidaemia and hypertension that markedly increases cardiovascular and diabetes risk^[1]. Reported incidence varies widely (3.7%–24.5%)^[2–5], partly due to different diagnostic criteria and study populations. Rural populations remain understudied despite potentially different exposure patterns and lifestyles.

Lifestyle and psychosocial factors are well-known determinants, but environmental factors—particularly air pollution—are increasingly recognised. Short-term PM_{2.5}, PM₁₀ and NO_x have been linked to elevated blood pressure^[6–8], while CO may lower it^[9]. Ozone has been associated with diastolic pressure^[10]. Longitudinal Chinese studies found positive associations between multiple pollutants and triglycerides (TG) and inverse associations with HDL-C^[11, 12]. Meta-analyses also link PM_{2.5}, PM₁₀ and NO₂ to type 2 diabetes^[13]. However, most studies focus on urban settings, and few have examined short-term multi-pollutant effects on individual MetS components in rural adults.

Therefore, we conducted a prospective cohort in rural Henan, central China, to estimate MetS incidence and to explore the short-term associations of six criteria air pollutants with SBP, DBP, TG, HDL-C and FBG.

Methods

Study population

This prospective cohort study, part of the National Key Research and Development Program "Precision Medicine Research" and registered at the China Clinical Trials Registry (ChiCTR-OOC-15006699, <https://www.chictr.org.cn/showproj.html?proj=11375>), was conducted in rural Xinxiang, Henan. Baseline data were collected in 2017 and follow-up in 2021. Using multistage cluster sampling, 12 villages were selected from two townships stratified by socioeconomic development. Among 10,690 baseline participants, after excluding deaths, losses to follow-up, urban residents, individuals <18 years, those with mismatched information, and 2,908 with baseline MetS (JIS criteria), 2,719 participants were included in the final analysis (**Figure 1**). The sample size had sufficient precision for estimating the 4-year cumulative incidence and adequate power for the subsequent association analyses^[14].

Air quality and meteorology

In 2021, data on six outdoor air pollutants (PM_{2.5}, PM₁₀, NO₂, SO₂, CO, O₃) were obtained from the Xinxiang Ecological Environment Bureau website(<https://sthjj.xinxiang.gov.cn/>), while daily mean temperature and relative humidity for Xinxiang came from the China Meteorological Data Network. The study period was May 19 to July 20, 2021, and all sampling sites were within 10 km of the environmental monitoring station.

Health measurements

Waist circumference (WL): After removing the jacket and breathing calmly, waist circumference was measured 1 cm above the navel using a standard measuring tape. The measurement was taken twice and averaged, recorded to the nearest 0.1 cm.

Blood pressure: After 5 minutes of quiet sitting, blood pressure was measured on the right arm using an Omron electronic sphygmomanometer (HEM-770A Fuzzy, Omron, Japan). Three readings were taken at ≥30-second intervals and averaged.

Biochemical indicators: (1) Blood collection and processing: After an 8–12-hour overnight fast, venous blood was drawn from the antecubital vein in a sitting position, collected into 5 mL sodium heparin anticoagulant tubes, mixed well, and centrifuged at

2000 g for 10 min. Serum was separated, stored frozen at –20°C, and transported on ice to the Yashijie Medical Center of Xinxiang Medical University. (2) Testing: Total cholesterol (TC), triglycerides (TG), high-density lipoprotein cholesterol (HDL-C), and low-density lipoprotein cholesterol (LDL-C) were measured by immunoturbidimetric assay on a Roche Cobas C501 automatic biochemistry analyzer. Fasting blood glucose (FBG) and uric acid were measured by spectrophotometry. FBG is reported in mmol/L and uric acid in μmol/L.

Definition of MetS

Primary definition followed the Joint Interim Statement (JIS) criteria^[15]. Sensitivity analyses used NCEP-ATP III^[16], IDF^[17] and CDS 2013 criteria (**Table 1**).

Table 1 Comparison of diagnostic criteria for MetS in different tissues

Diagnostic indicators		JIS	NCEP-ATP III	IDF	CDS (2013)
Waist circumference (cm)	Male	≥85	≥90	≥90	≥90
	Female	≥80	≥80	≥80	≥85
Fasting TG (mmol/L)		≥1.70	≥1.69	≥1.70	≥1.70
Fasting HDL-C (mmol/L)	Male	<1.03	<1.03	<1.00	<1.04
	Female	<1.30	<1.29	<1.30	
Blood pressure (mmHg)	SBP	≥130	≥130	≥130	≥130
	DBP	≥85	≥85	≥85	≥85
Blood glucose (mmol/L)	Fasting	≥5.6	≥5.6	≥5.6	≥6.1
	2h after meal	-	-	-	≥7.8
Diagnostic criteria		Three or more abnormalities	Three or more abnormalities	Central obesity + the remaining two or more abnormalities	Three or more abnormalities

Note: Each diagnostic criterion, such as blood pressure, systolic blood pressure (SBP) and diastolic blood pressure (DBP) are logically related as or (and), as long as SBP is greater than a certain value or (and) DBP is greater than a certain value, the diagnostic criterion is met; if taking blood pressure lowering drugs or treatment, the diagnostic criterion is also met; other diagnostic indicators such as blood sugar, waist circumference, etc. have similar interpretations.

Covariates

We adjusted for sex, age, education, marital status, income, occupation, religion, tea/chilli consumption, diet, smoking, alcohol, depression, sleep, physical activity, family history of hypertension/diabetes, comorbidity index, and moving averages of temperature and humidity for the same lag period.

Statistical analysis

Data were double-entered using Epidata 3.1 and analyzed with SPSS 20.0; missing values were imputed via the EM normal method. To address potential lag effects, air pollutant concentrations were examined as single-day lags (lag0–lag7, the daily mean from the examination day back to 7 days prior) and multi-

day cumulative lags (lag01–lag07, rolling means of 2–8 days). Spearman correlations between these lagged exposures and SBP, DBP, TG, HDL-C, and FBG in MetS patients were assessed and plotted using the “pheatmap” package in R 4.1.1. Associations were estimated with generalized linear models (Gaussian family, identity link), adjusting for sex, age (continuous), education, marital status, per capita monthly income, occupation, religion, tea and chili consumption, dietary pattern, smoking and alcohol use, depression, sleep, physical activity, family history of hypertension and diabetes, comorbidity index, and moving averages of temperature and relative humidity over the same lag period. All models were run in STATA 17.0. Results represent the change in each outcome per one-standard-deviation increase in pollutant concentration.

Results

Incidence of MetS under different diagnostic criteria

Baseline included 10,690 participants. The study population selection process is illustrated in **Figure 1**, and the incidence and age-standardised rates under the four criteria (JIS, NCEP-ATP III, IDF and CDS) are summarised in **Table 2**.

Table 2 Incidence of MetS under different diagnostic criteria

Diagnostic criteria	Total number of people	Number of morbidity	Cumulative incidence rate (%)	Average annual incidence rate (%)	Standardized incidence rate (%)
JIS	2,719	434	16.0	4.0	12.64
NCEP-ATP III	2,888	434	15.0	3.75	11.95
IDF	3,169	426	13.4	3.35	10.68
CDS (2013)	3,645	477	13.1	3.275	10.19

Abbreviations: JIS, Joint interim statement.NCEP-ATP III, National Cholesterol Education Program Adult Treatment Panel III. IDF, International Diabetes Federation Working Group on Epidemic Prevention. CDS (2013),the 2013 Chinese Diabetes Society.

Short-term air pollutant and meteorological data characteristics

Of the 10,690 baseline participants, the selection process by each MetS criterion is shown in **Figure 1**, and the corresponding incidence and age-standardised rates are presented in **Table 3**.

Table 3. Concentration of pollutants and meteorological parameters

		Average number	Standard deviation	Minimum value	Maximum value
Contaminants ($\mu\text{g}/\text{m}^3$)					
	PM _{2.5}	31.86	16.94	7	106
	PM ₁₀	79.06	42.17	21	276
	NO ₂	20.21	7.24	7	39
	SO ₂	10.94	3.43	2	18
	CO	0.60	0.19	0.3	1.3
	O ₃	123.00	36.56	51	202
Meteorological factors					
Average temperature °C		27.7	2.16	23.2	31.7
Average relative humidity (%)		65.00	18.65	26	100

Correlation of air pollutants with metabolic syndrome components

Overall, the exposure–response correlations between short-term air pollutants and MetS components were weak. The strongest positive associations were observed for SBP with PM_{2.5} lag7 ($r=0.040$), DBP with PM_{2.5} lag7 ($r=0.039$), TG with O₃ lag7 ($r=0.089$), HDL-C with PM_{2.5} lag3 ($r=0.034$), and FBG with O₃ lag0 ($r=0.050$). The most pronounced negative correlations were found for SBP with PM_{2.5} lag4 ($r=-0.072$), DBP with O₃ lag06 ($r=-0.084$), TG with PM₁₀ lag06 ($r=-0.122$), HDL-C with O₃ lag01 ($r=-0.093$), and FBG with O₃ lag01 ($r=-0.256$) (**Figure 2**).

Single-lag and cumulative-lag effects on MetS components

SBP: In single-lag models, PM₁₀ (lag1, 2, 5) and SO₂ (lag1, 3) were positively associated; PM_{2.5} (lag4), NO₂ (lag4), CO (lag4–6), and O₃ (lag3–5) were inversely associated. In cumulative models, PM₁₀ (lag07) and SO₂ (lag03–06) remained positive, while O₃ (lag05–07) was negative. The largest effect was observed for SO₂ at lag06 (+33.7%, 95% CI: 14.6%–146.5% per SD) (**Figure 3A**).

DBP: Positive associations were found for PM_{2.5} (lag7), PM₁₀ (lag2, 7), and SO₂ (lag2–4) in single-lag models; cumulative SO₂ (lag03–07) remained positive, while PM_{2.5} (lag04–05), CO (lag01, 03–05), and O₃ (lag05) were inversely associated. The largest effect was SO₂ at lag07 (+24.4%, 95% CI: 9.9%–105.6%) (**Figure 3B**).

TG: Negative associations were observed for PM_{2.5} (lag3, 5, 7), PM₁₀ (lag3, 5), SO₂ (lag5), and NO₂ (lag5) in single-lag models; cumulative PM₁₀ (lag05) was also inversely associated. Effect sizes were small (e.g., PM_{2.5} lag7: -0.2%, 95% CI: -0.7% to -0.1%) (**Figure 3C**).

HDL-C: In single-lag models, SO₂ (lag6) was positively associated, whereas CO (lag1) and O₃ (lag0-1) were negatively associated. In cumulative models, SO₂ (lag03-05), CO (lag01-03), and O₃ (lag01-03) were consistently negatively associated. The largest decrease was observed for SO₂ at lag05 (-0.5%, 95% CI: -1.9% to -0.1%) (**Figure 3D**).

FBG: Single-lag models showed negative associations for PM_{2.5} (lag0-4, 6-7), PM₁₀ (lag0-6), SO₂ (lag3-7), CO (lag1, 3), and O₃ (lag5). In cumulative models, NO₂ (lag01-07) was positively associated, with a maximum increase of +0.8% at lag07 (95% CI: 0.5%-3.4%); PM_{2.5}, PM₁₀, and O₃ remained negatively associated (**Figure 3E**).

Sensitivity analysis

Using alternative MetS criteria (NCEP-ATP III, IDF and CDS), the directions and magnitudes of associations remained essentially unchanged, confirming the robustness of the findings (**Supplementary Figure S1**)).

Discussion

This is among the first studies to estimate MetS incidence and simultaneously examine short-term multi-pollutant effects on five metabolic components in rural Chinese adults. The observed 4-year cumulative incidence (16.0% by JIS) aligns with findings from recent rural population-based studies^[5].

Our main finding is that cumulative exposures showed more consistent effects than single-day lags. PM₁₀ and SO₂ were positively associated with SBP and DBP; SO₂, CO and O₃ inversely associated with HDL-C; cumulative NO₂ was linked to increased FBG. These effect sizes are modest at the individual level but may be relevant at population scale given universal exposure.

Some discrepancies with prior studies deserve mention. We observed negative associations between PM_{2.5} and SBP in certain single-day lags, contrary to positive findings^[6, 7]. This may be due to non-linear exposure-response, different PM chemical composition in rural areas (biomass vs. traffic), or different activity patterns. For SO₂, long-term studies have reported positive blood pressure associations^[18, 19], while short-term effects have been inconsistent^[20]. For NO₂, previous findings also showed mixed results^[21-23] CO exposure has been linked to hypotension in some studies^[24, 25] but not all^[26, 27]. The opposite directions between single-day and cumulative lags (e.g., SO₂ and HDL-C) suggest that acute and delayed effects may involve distinct pathways—oxidative stress/inflammation versus metabolic adaptation. The cumulative positive effect of NO₂ on FBG, despite null/negative single-day estimates, indicates sustained exposure may impair glucose homeostasis, consistent with some meta-analyses^[13]

but not all ^[28, 29]. Associations between O₃ and FBG have been variably reported, with some studies showing positive ^[30-32] and others negative ^[14, 33, 34] or null ^[35-37].

Limitations: First, exposure from fixed-site monitors may cause misclassification. Second, the spring-summer study period limits generalisability to other seasons. Third, indoor sources and individual mobility were not assessed. Despite these, our findings provide novel epidemiological evidence for rural populations and highlight that even low-level short-term pollution may affect metabolic health.

Conclusion

The 4-year cumulative incidence of MetS among residents of rural Xinxiang City was 16.0%, with an average annual prevalence of 4% and an age-specific prevalence of 12.64%. The correlation between short-term exposure to air pollutants and constitutive indicators of MetS was weak. Increased concentrations of PM₁₀, SO₂ were associated with increased systolic blood pressure; increased concentrations of PM_{2.5}, PM₁₀, SO₂ were associated with increased diastolic blood pressure; increased concentrations of SO₂, CO, O₃ were associated with decreased HDL-C; increased NO₂ concentration was associated with a rise in FBG. This study is the first to systematically characterize the lag patterns of short-term multi-pollutant exposure on multiple metabolic indicators among rural adults in China. The findings highlight the necessity of targeted environmental health interventions for rural populations and provide epidemiological evidence for future mechanistic investigations.

Future research should integrate individualized exposure monitoring (e.g., personal wearable devices) with biomarkers (e.g., inflammatory cytokines) to further elucidate how differences in pollutant components and exposure patterns lead to varying effects across urban and rural populations. Additionally, the application of more sophisticated time-series methods such as distributed lag nonlinear models may facilitate a more precise delineation of exposure-response curves for different health outcomes.

Abbreviations

CI: Confidence interval; MetS: Metabolic syndrome; SBP: systolic blood pressure; DBP: diastolic blood pressure; TG: triglyceride; FBG: fasting blood glucose; LDL-C: low-density lipoprotein cholesterol; HDL-C: high density lipoprotein-cholesterol; NCEP-ATP III: National Cholesterol Education Program Adult Treatment Panel III; IDF: International Diabetes Federation; JIS: the Joint interim statement; CDS: Chinese Diabetes Society.

Declarations

Acknowledgements

We sincerely thank all the study participants.

Funding

National Natural Science Foundation of China (grant number: 81961128031; 81573112).

Availability of data and materials

There are no supporting data presented and linked with this study. Supporting data is available from the authors on request.

Competing interests

The authors declare that there are no competing interests.

Consent for publication

Not applicable.

Ethics approval and consent to participate

This study was approved by the Zhengzhou University Life Science Ethics Committee (Code: [2016] MEC (S128)) and conducted in accordance with the 1975 Declaration of Helsinki. Informed consent was obtained from all participants before enrollment. No participants were under 16 years of age; therefore, consent from parents or legal guardians was not applicable.

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Figures

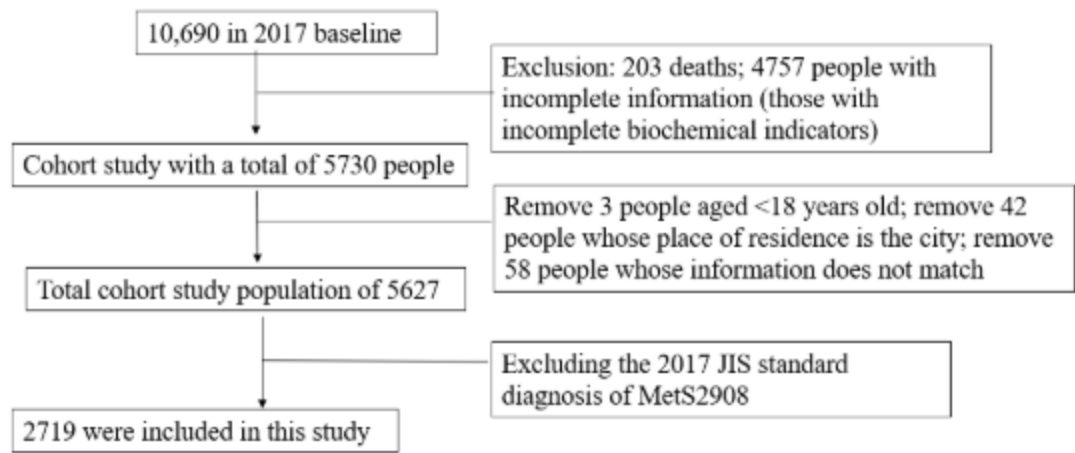


Figure 1

Flow chart of the study object determination

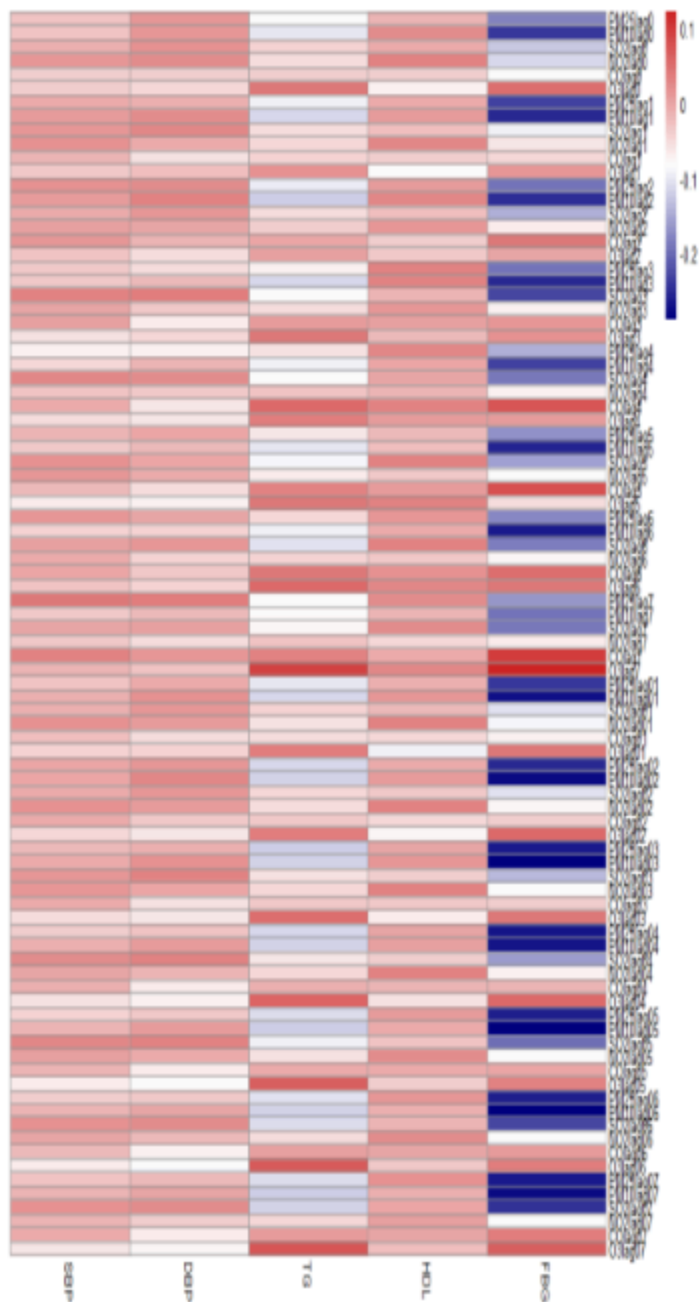


Figure 2

Correlation between short-term exposure to air pollutants and metabolic syndrome components

Abbreviations: JIS, Joint interim statement; NCEP-ATP III, National Cholesterol Education Program Adult Treatment Panel III; IDF, International Diabetes Federation; CDS, Chinese Diabetes Society.

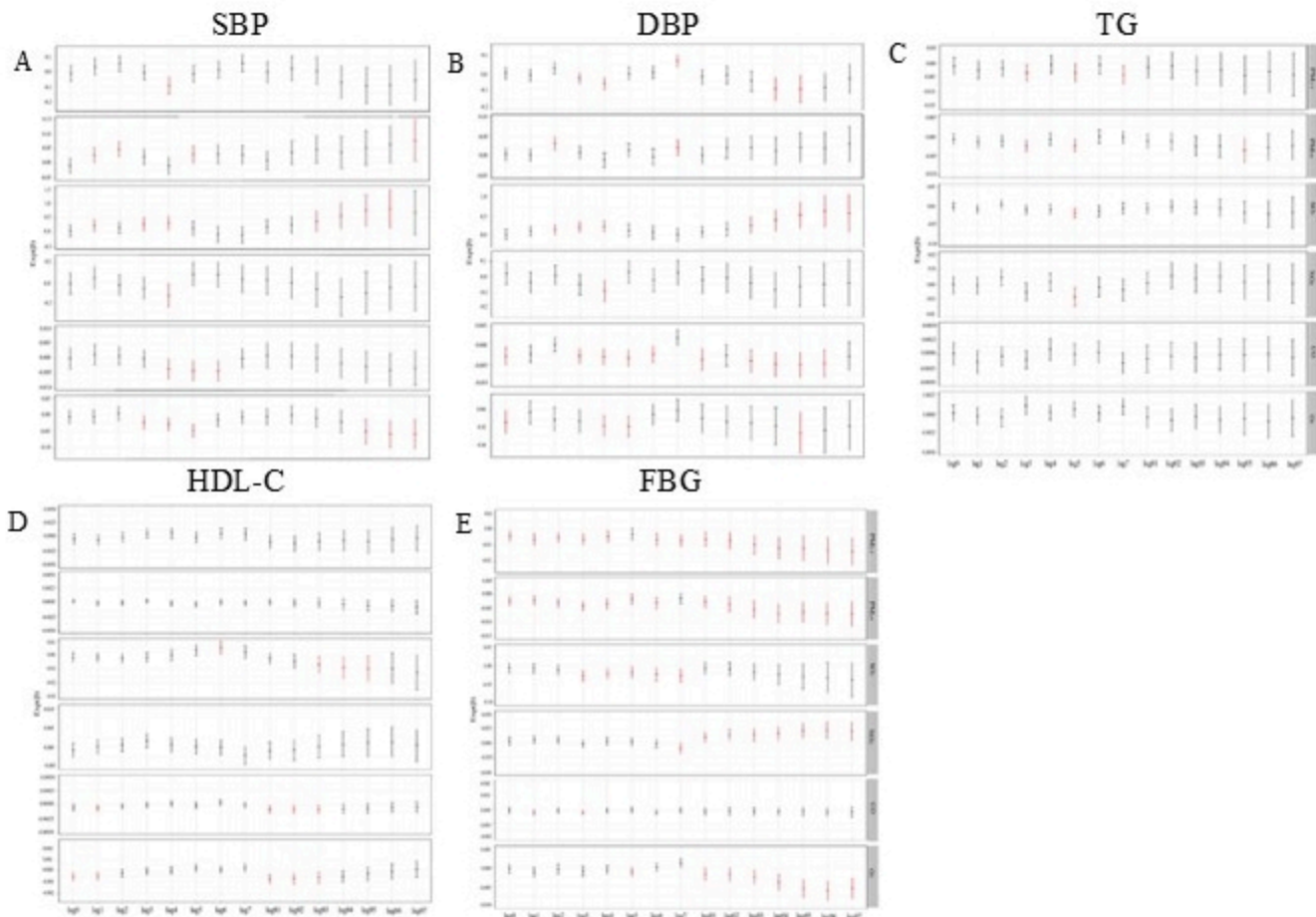


Figure 3

Effects of short-term exposure to air pollutants on blood pressure and metabolic parameters.

(A) Systolic blood pressure (SBP); (B) Diastolic blood pressure (DBP); (C) Triglycerides (TG); (D) High-density lipoprotein cholesterol (HDL-C); (E) Fasting blood glucose (FBG).

Figure S1 Sensitivity analysis of short-term exposure to air pollutants on biochemical indicators of MetS patients

Supplementary Files

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