Long-term effects of ambient PM_{2.5} on hypertension in multi-ethnic population from Sichuan province, China: a study based on 2013 and 2018 health service surveys

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Research

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Abstract

Background

Hypertension, a major risk factor of many severe chronic diseases and leading cause of global disease burden, is reported associated with exposure to $PM_{2.5}$. China's high $PM_{2.5}$ pollution level has become a major public health issue. However, existing studies from China on the effect of $PM_{2.5}$ exposure on hypertension have got inconsistent results with very limited investigation into the multi-ethnic people. This study adds multi-ethnic evidence from Sichuan Province, southwestern China, and assesses ethnic differences of $PM_{2.5}$ exposure effect on hypertension.

Methods

We pooled large cross-sectional data from two surveys conducted in Sichuan province in 2013 and 2018 to exam the effect of long-term exposure to $PM_{2.5}$ on prevalence of hypertension in adults aged 30 years old and above. Community-specified annual $PM_{2.5}$ concentration was estimated using satellite data. Logistic regression was applied to examine the association between long-term exposure to $PM_{2.5}$ and hypertension prevalence in the whole population, specific ethnic populations and population (including Han and ethnic minority people) living in same areas.

Results

31462 participants with an average age of 56 years old were included. The average exposure concentration was $32.8 \mu g/m^3$. The proportions of the Han, the Tibetan, the Yi, and other ethnic people were 89.2%, 7.3%, 3.2%, and 0.3%, respectively. The adjusted odds ratio (OR) was 1.08 (95% CI, 1.04–1.12) for a $10 \mu g/m^3$ $PM_{2.5}$ concentration increment for the whole population. The adjusted ORs for the Han, the Tibetan, and the Yi were 1.08 (95% CI, 1.04–1.12), 0.03 (95% CI, 0.00–0.27), and 1.75 (95% CI, 1.28–2.38) for a $10 \mu g/m^3$ $PM_{2.5}$ concentration increment, respectively. Stratification analysis found stronger associations in participants with chronic diseases and Yi minority population.

Conclusion

Long-term exposure to $PM_{2.5}$ may increase the risk of hypertension prevalence in Chinese multi-ethnic adults. Stronger associations were found in people with chronic disease and Yi minority group.

Introduction

High blood pressure and hypertension are recognized as the risk factors for many severe non-

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vascular disease, stroke, kidney cancer, etc.¹. In 2017, high

systolic blood pressure (SBP) was reported to be the first leading cause of global disease burden, accounting for 11.4 million deaths and 218 million DALYs². The prevalence of hypertension in China has increased with the development of economy and aging of the population³. In parallel, poor ambient air quality in China has become a serious public health issue. Previous studies have found that both short-term and long-term exposure to PM_{2.5} are associated with elevations in blood pressure. Compared with short-term exposure, long-term exposure seems to have stronger effects on high blood pressure and hypertension^{4–10}.

However, the evidence from epidemiology study on the long-term effect of PM_{2.5} on hypertension remains inconsistent. Several recent studies suggested that long-term exposure of higher PM_{2.5} concentration was related to increased prevalence of hypertension^{6–10} and that improvement of PM_{2.5} exposure was associated with a decreased incidence of hypertension¹¹, while other studies reported no significant association between long exposure of PM_{2.5} and hypertension^{12,13}. Variations in subject characteristics, geographical settings, pollutant sources and compositions, measurement of exposure etc. may be responsible for the inconsistency. Thus, further study on diverse population is needed.

Striking ethnic/racial differences in abnormal blood pressure or other related adverse cardiovascular outcomes attributed to PM_{2.5} exposure have been reported, but the results were inconclusive. A study of 132224 adults based on the USA 1995–2005 National Health Interview Survey showed that PM_{2.5} was positively associated with prevalent self-reported hypertension (OR of 1.05 for a 10 µg/m³ increase). This association varied from different race/ethnicity which was statistically significant in the White but not the Black or the Hispanic¹⁴. But another American multi-ethnic (MESA) cohort study found that the Black showed stronger association than the White even after adjustment for SES¹⁵.

Ethnicity/race is a synthetic index which can reflect accumulative information of multiple social and health related factors. Researchers note that examining the cumulative effects of numerous factors is vital when investigating vulnerability to environmental health issues¹⁶. Ethnicity/race could be treated as a surrogate of a cluster of unmeasured confounders including genetic heterogeneity and cultural or religious differences. However, the relationship among long-term exposure, Ethnicity/race and hypertension is complicated. Ethnicity/race has interaction with many social, psychosocial and environmental factors. In the US and Europe, minority neighborhood tends to be exposed to heavier air pollution, indicating that ethnic/racial difference may result from residential segregation^{15,17,18}. Meanwhile, racial segregations are often lower-income communities where minority groups are often with lower SES and suffer related noise, poverty and other stressors. This cluster of social, psychosocial and environmental disadvantages would lead to poor health outcomes¹⁹. As a result, it is particularly important to disentangle the combined effect of Ethnicity/race, other social/ psychosocial factors and environmental exposure, and identify modifiable exposures so as to understand how to best protect susceptible populations and improve overall population health¹⁹.

Although studies based on Chinese population were conducted, the evidence from multi-ethnic population was limited. Most related studies conducted in China didn't consider the ethnicity of subjects^{6, 7, 10, 20}, or loosely divided subject into Han and non-Han groups²¹. However, different ethnic groups have their own customs, culture, living habits, and geographic contexts. If combining all the minority groups together, the accuracy of study results would surely be lowered. Health inequality in relation to China's disproportionate air pollution distribution has started to draw academic attention, and their studies reported that socioeconomic factors such as urbanization, health recourse, and house consumption could have impacts on both the health inequality and disproportionate air pollution distribution^{22, 23}. Those studies were based on provincial level rather than individual level, so their results could be quite limited when exploring how social and environmental factors are related to ethnic/racial disparity from an individual perspective. Different from western countries, China's ethnic/racial minority groups generally live in low PM_{2.5} pollution areas but some of the groups are with high prevalence of hypertension²⁴. In western China, the Tibetan and the Yi are two major ethnic minority groups. Compared with Han group, most of Tibetan and Yi group live in rural areas and tend to be of lower education attainment and poorer economic level²⁵. In addition, the main domestic fuel of rural areas is solid fuel including coal and biomass, which could create serious indoor air pollution and expose people to high health risks².

From the above discussion, this study aims to (1) evaluate the association between long-term exposure of PM_{2.5} and hypertension in an multi-ethnic population; (2) evaluate whether the association between PM_{2.5} exposure and hypertension are modified by social and psychosocial determinants of health, including ethnicity, SES (education, income), and health related factors (comorbidity, anxiety/depression); (3) detect the potential cause of ethnic differences by exploring the interaction of ethnicity and other social and environmental factors. The results may shed clues on the ethnic disparity of long-term PM_{2.5} exposure effect on hypertension and provide knowledge for identifying vulnerable populations and targeting intervention measurements from an ethnic perspective.

Methods

Setting

Sichuan province is located in Southwest China ranging from 26°30' to 34°190'N and from 97°300' to 108°310'E. 73.56% of its area is covered with mountains of which an average height is over 5000 m above the sea level. This is a province surrounded by highlands and mountains, including Tibetan Plateau, Yunnan-Guizhou Plateau, Daba Mountains, and Wu Mountains^{26, 27}. Its complex and unique geographic characteristics block pollutant diffusion, which leads to a gradient spatial PM_{2.5} distribution with the maximum in Sichuan Basin and the minimum in its northwest region²⁸. Sichuan Basin, the eastern part of Sichuan province, is one of the highest PM_{2.5}-concentration regions in China. The annual average PM_{2.5} concentrations in Sichuan Basin during 2004 and 2013 are generally $\geq 85 \mu\text{g}/\text{m}^3$ ²⁹.

Because of the severe PM_{2.5} pollution, the government has taken a series of measures to prevent and

control PM_{2.5} and its precursors³⁰. Nevertheless, PM_{2.5} remains the major pollutant which plays a dominant role in Sichuan region³¹.

Sichuan is the home for about 5 million ethnic minority population³². Yi (2.6 million), Tibetan (1.5 million) and Qiang (0.3 million) ethnic groups account for the majority³³. Their SESs, lifestyles and living conditions vary greatly. Sichuan is also a province with unbalanced social and economic developments. There is not only a megacity (the capital of Sichuan province, Chengdu), but also remote rural areas with three minority autonomous prefectures (Liangshan Yi Autonomous Prefecture, Aba Tibetan Autonomous Prefecture, and Ganzi Tibetan Autonomous Prefecture). These conditions may exert a non-negligible effect on the association between PM_{2.5} exposure and hypertension prevalence, but related evidence from Sichuan province and southwest China is hardly sufficient.

Data

The research data comes from the Fifth and Sixth Health Services Surveys (HSSs) conducted in Sichuan Province in 2013 and 2018 which are part of National Health Services Surveys (NHSSs). NHSS is a regular survey implemented by national and local governments every five years. The purpose of NHSS is to understand the health status of the population, their needs and demands for healthcare services, and the utilization and costs of healthcare services in a systematic fashion. A multi-stage stratified random cluster sampling method has been adopted to draw 14 urban districts/ rural counties randomly in Sichuan Province. In each district/county, 5 subdistricts/townships were randomly selected. In each subdistrict /township, 2 communities/villages were randomly selected. And in each community/village, 60 households were randomly selected. The sampling designs of the Fifth and Sixth HSS were the same, but Litang was replaced by Danba in 2018. Therefore, 15 districts/counties were included in this study.

Among the 15 districts/counties, there were 3 ethnic minority counties according to Chinese Government's categorization³⁴: two Tibetan counties (Litang and Daba) and one Yi county (Yanyuan). The rest 12 were Han districts/counties.

The Fifth and Sixth HSS participants totaled 22795 and 21047. This study combined both survey data for analysis to detect the effect differences among Han, Tibetan, and Yi ethnic groups. Subjects aged 30 years and older were included.

Hypertension

Participants with at least one of the following characteristics were considered to be of hypertension: 1) being physician-diagnosed with hypertension within 6 months prior to the survey; 2) being physician-diagnosed with hypertension over 6 months prior to survey and having taken measures to control blood pressure within 6 months prior to survey.

Air Pollution

Outdoor PM_{2.5} concentrations from 2008 to 2016 were estimated with the Geographically Weighted Regression (GWR) model developed by van Donkelaar et al (2016) ³⁵. This model combined satellite-derived aerosol optical depth (AOD) data and surface monitor data, and conducted simulations with GEOS-Chem chemical transport model to provide a long-term average ambient PM_{2.5} concentration at around 10km × 10 km resolution with R² of 81%.

Outdoor PM_{2.5} concentrations in 2017 were estimated with Bayesian Spatial Model developed by Zhang et al (the article is being submitted). Based on satellite-derived aerosol optical depth (AOD) data and surface monitor data, this model conducted simulations with hierarchical Bayesian approaches to estimate PM_{2.5} at 1km × 1 km resolution. R² and root mean squared error (RMSE) of 10-fold cross validation for the model were 87% and 1.167.

Community/village locations were geocoded with Google Earth. Estimated annual ambient PM_{2.5} concentrations were mapped to participants in the corresponding communities/villages.

The annual average PM_{2.5} concentrations for each location from 2008 to 2012 (the Fifth HSS) and from 2013 to 2017 (the Sixth HSS) were used as the estimated surrogate of exposure.

Covariates

Face-to-face interviews with paper (used in 2013) or electronic (used in 2018) questionnaires were applied to collect participants' demographic, socioeconomic and lifestyle information, such as age, sex, ethnicity, residence, marital status, education, annual household income, body mass index (BMI), smoking status, drinking status, physical activity, etc. Questionnaire structures of the Fifth HSS and the Sixth HSS were basically the same, but some items have been modified or deleted. The item about ethnicity in 2013 national questionnaires didn't include the option of "Yi" as 2018 did. "Yi" was included into the option of "Others" in 2013. However, 2018 data showed that over 94% (675/717) of the people who chose "Others" belonged to the Yi minority group. On-site investigation experience also verified that the Yi accounted for most of the "Others". Thus, "Others" in ethnic options from the 2013 questionnaire was coarsely treated as "Yi" in this study. The item about domestic fuel type was deleted in the questionnaire of 2018.

In this study, ethnicity options were organized into four categories: Han, Tibetan, Yi and Others.

BMI was divided into four categories: underweight (< 19.5 kg/m²), normal weight (19.5 ~ 24.0 kg/m²), overweight (24.0 ~ 28.0 kg/m²), and obesity (≥ 28.0 kg/m²) according to China's weight criteria ³⁶. EQ-5D-3L was used to collect information about health-related quality of life. Anxiety/depression symptom and visual analogue scale (VAS) were part of EQ-5D-3L. Anxiety/depression symptoms were divided into 3 levels as "not at all", "moderate" and "severe". VAS ranged continuously from 0 to 100. Comorbidity was examined by a dyadic measure ("having other chronic diseases except hypertension" or "having no other chronic diseases except hypertension").

Education status was categorized as “no formal education”, “primary school”, “middle school” and “high school or above”.

Average annual salt sales volume of each district/county for 5 years preceding the survey and the population of each district/county were collected from Sichuan Provincial Statistics Yearbook, and then per capital annual salt sales volume was calculated by averaging annual salt sales volume per person in kg.

Statistical Analysis

After univariate variable analyses, multivariate logistic regression models were fit to control potential confounding factors, including basic characteristics (age, sex, and ethnicity), health-related factors (BMI, anxiety/depression, comorbidity VAS and per capital annual salt sales of each district/county), SES index (education status, per capital annual household income). The missing data was excluded as less than 5%.

Stratified analyses were conducted to examine whether the association between long term exposure of $PM_{2.5}$ and hypertension prevalence could be modified by age(< 60 and ≥ 60), sex (male and female), BMI (normal, overweight and obesity), comorbidity (yes and no), and ethnicity (Han, Tibetan, Yi).

Based on the results of stratified analyses by ethnicity, the potential cause of ethnic disparity was further explored. In this study, the 12 Han districts/counties together were regarded as Han area, 2 Tibetan counties as Tibetan area and 1 Yi county as Yi area. It was assumed that environmental/social characteristics of the Han and minority groups who live in same area were similar. To control unobserved environmental/social factors, the different effects on the Han and minority groups were analyzed based on population who reside in the same Han, Tibetan and Yi area respectively. As few minority people reside in Han area, only population in Tibetan area and Yi area were taken into analysis in terms of ethnicity. In our sampled sites, Yi area had only one county (Yanyuan County) where the range of $PM_{2.5}$ concentration is too narrow to test any association. As survey results indicated that except those from Yanyuan County, around 90% of the rest Yi people were from Xi District, this district close to Yanyuan County and with a large number of Yi people, was included into the original Yi area.

Furthermore, previous studies suggested that domestic fuel type could modify the effect⁶. Since clean domestic fuel was disproportionately distributed by ethnicity, it can be one of important factors in relation to ethnic differences. For no domestic fuel type data was collected in 2018, the synergy effect of ambient $PM_{2.5}$ exposure and indoor fuel type was examined only based on the data of 2013.

Sensitivity analyses were performed. First, the association was tested using different measures of exposure, average $PM_{2.5}$ concentrations for 1–4 years before the survey. Second, the association was tested after adjustment of residence location (urban or rural area) and survey year. Third, the association was tested by using the Fifth and Sixth HSS data separately.

Results

A total of 31462 participants were included with hypertension prevalence of 15.7%. 28050 participants were Han, 2288 participants were Tibetan, 1013 participants were Yi, and 111 participants belonged to other ethnic groups. The average age of participants was 55.6 years old with an annual mean $PM_{2.5}$ exposure concentration of $32.8 \mu g/m^3$. The distributions of $PM_{2.5}$ concentration in 2013 and 2018 were similar as shown in Fig. 1. Detailed $PM_{2.5}$ exposure concentrations were listed in Table S1. Qingyang District, one the five main urban districts of the capital of Sichuan Province, was the most polluted area with average $PM_{2.5}$ concentration of $55.3 \mu g/m^3$, which was also with highest hypertension prevalence of 23.7%. A low level of $PM_{2.5}$ concentration was observed in minority sample sites. The average exposure concentration in Yanyuan County of Yi Autonomous Prefecture was $9.8 \mu g/m^3$. The concentrations of those two Tibetan counties were even lower. In Tibetan area, the concentrations of Danba and Litang were $5.3 \mu g/m^3$ and $2.4 \mu g/m^3$, respectively. The prevalence of hypertension in those three minority counties was also relatively low (Yanyuan County: 5.6%; Danba County: 13.8%; Litang County: 15.9%). In general, $PM_{2.5}$ concentration and hypertension prevalence of each sample district/county was positively related with a correlation coefficient of 0.54 ($P=0.04$). $PM_{2.5}$ exposure and hypertension prevalence distribution at a district/county level was shown in Fig. 2.

Figure 1 The Distribution of $PM_{2.5}$ Concentration

Figure 2 The $PM_{2.5}$ Concentration and Prevalence of Sample Districts/Counties

Grouped by hypertension and non-hypertension, basic characteristics of participants were presented in Table 1. The hypertension participants were older than the non-hypertension participants (65.4 years versus 53.7 years) and they were exposed to higher ambient $PM_{2.5}$ ($34.5 \mu g/m^3$ versus $32.5 \mu g/m^3$). Compared with the referent group, the urban residents and the Han population accounted for a higher proportion in both hypertension and non-hypertension groups. The hypertension patients were more likely to be overweight (32.21% versus 23.46%) and obese (10.09% versus 4.89%), and they were more likely to have symptoms of anxiety/depression (19.31% versus 12.25% for moderate; 2.00% versus 1.17% for severe). Among hypertension patients, 59.9% took health checkup in the previous year, far exceeding non-hypertension people (45.6%). As for health-related behaviors, hypertension participants were less likely to brush teeth every day (81.20% versus 85.60%), smoke (20.86% versus 29.24%) and drink alcohol (18.33% versus 26.15%); on the contrast, they were more likely to do physical activities (41.97% versus 31.88%). The hypertension patients had a higher income than non-hypertension subjects (45.67% versus 42.35% for income > quantile 60).

Table 1

Comparison of Sociodemographic and Major Risk Factors Between Hypertension and Non-hypertension Participants

Variables	Referent group (n = 26516)	HP group (n = 4946)	P value
Age (years); mean(s.d.)	53.7(13.4)	65.4(11.1)	< 0.001
PM _{2.5} (µg/m ³); mean(s.d.)	32.5(14.1)	34.5(13.4)	< 0.001
Sex; n(%)			
Male	12956(48.9)	2282(46.1)	0.001
Female	13560(51.1)	2664(53.9)	
Marital status; n(%)			
Single	3653(13.8)	789(16.0)	0.004
Married	15969(60.2)	2903(58.7)	
Others	6894(26.0)	1254(25.4)	
Ethnicity; n(%)			
Han	23491(88.6)	4559(92.2)	< 0.001
Tibetan	1956(7.4)	332(6.7)	
Yi	969(3.7)	44(0.9)	
Others	100(0.4)	11(0.2)	
Residence; n(%)			
Urban area	13166(49.7)	2662(53.8)	< 0.001
Rural area	13350(50.4)	2284(46.2)	
Education; n(%)			
No formal education	2767(10.4)	708(14.3)	< 0.001
Primary school	16047(60.5)	2733(55.3)	
Middle school	4874(18.4)	1086(22.0)	
High school or above	2828(10.7)	419(8.5)	
employment; n(%)			

HP: hypertension; PM_{2.5}: particulate matter with an aerodynamic diameter ≤ 2.5 µm; BMI: body mass

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Variables	Referent group (n = 26516)	HP group (n = 4946)	P value
employed	18836(71.0)	2359(47.7)	< 0.001
retired	2626(9.9)	1213(24.5)	
Other	5054(19.1)	1374(27.8)	
Per capital Household income; n(%)			
Q1	4790(18.1)	938(19.0)	< 0.001
Q2	5113(19.3)	904(18.3)	
Q3	5379(20.3)	844(17.1)	
Q4	5469(20.6)	960(19.4)	
Q5	5757(21.7)	1298(26.3)	
missing	8(-)	2(-)	
BMI; n(%)			
Underweight	2776(10.5)	401(8.1)	< 0.001
Normal weight	16222(61.2)	2453(49.6)	
Overweight	6220(23.5)	1593(32.2)	
Obese	1297(4.9)	499(10.1)	
missing	1(-)	-	
Smoking; n(%)	7500(29.2)	972(20.9)	< 0.001
Alcohol consumption; n(%)	6912(26.2)	904(18.3)	< 0.001
Physical activity; n(%)	8453(31.9)	2076(42.0)	< 0.001
Health check; n(%)	12088(45.6)	2963(59.9)	< 0.001
Brush teeth every day; n(%)	22698(85.6)	4016(81.2)	< 0.001
anxiety/depression; n(%)			
not at all	22960(86.6)	3892(78.7)	< 0.001
moderate	3247(12.3)	955(19.3)	
severe	309(1.2)	99(2.0)	

HP: hypertension; PM_{2.5}: particulate matter with an aerodynamic diameter $\leq 2.5 \mu\text{m}$; BMI: body mass

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Variables	Referent group (n = 26516)	HP group (n = 4946)	<i>P</i> value
VAS; mean(s.d.)	74.4(16.6)	66.0(17.9)	< 0.001
comorbidity; n(%)	7882(29.7)	2441(49.4)	< 0.001
HP: hypertension; PM _{2.5} : particulate matter with an aerodynamic diameter ≤ 2.5 μm; BMI: body mass index.; VAS: visual analogue scale.			

Table 1 Comparison of Sociodemographic and Major Risk Factors Between Hypertension and Non-hypertension Participants

Table 2 showed the results of comparison of sociodemographic and major risk factors among different ethnicities. The average annual PM_{2.5} concentrations of the Han, Yi and Tibetan people were 35.9ug/m³, 11.9 ug/m³, and 3.9 ug/m³, respectively ($P < 0.0001$). Distribution of PM_{2.5} concentrations for different ethnic-group was shown in Fig. 3. SES of the Han were higher than the other two minority groups. Yi minority group was of lowest SES among the three ethnic groups. Over 80% of Yi people had only primary school education attainment and per capital household income of over 50% Yi participants ranked below the 40th percentile of all participants. Besides, Yi minority group had a relatively higher proportion with adverse health-related behaviors like smoking, while a lower proportion with beneficial health-related behaviors like physical activities and health check.

Table 2
Comparison of Sociodemographic and Major Risk Factors by Ethnicity

Variables	Han (n = 28050)	Tibetan (n = 2288)	Yi (n = 1013)	Pvalue
	Mean/n	Mean/n		
HP; n(%)	4559(16.3)	332(14.5)	44(4.3)	< 0.001
Age (years); mean(s.d.)	56.3(13.6)	49.7(13.4)	48.4(12.6)	< 0.001
PM _{2.5} (μg/m ³); mean(s.d.)	35.9(11.1)	3.9(2.5)	11.9(7.3)	< 0.001
Sex; n(%)				
Male	13649(48.7)	1064(46.5)	482(47.6)	0.119
Female	14401(51.3)	1224(53.5)	531(52.4)	
Marital status; n(%)				
Single	3129(11.2)	1023(44.7)	283(27.9)	< 0.001
Married	17085(60.6)	1101(48.1)	609(60.1)	
Others	7836(27.9)	164(7.2)	121(12.0)	
Residence; n(%)				
Urban area	15659(55.8)	5(0.2)	114(11.3)	< 0.001
Rural area	12391(44.2)	2283(99.8)	899(89.7)	
Education; n(%)				
No formal education	2746(9.8)	442(19.3)	268(26.5)	< 0.001
Primary school	17407(62.1)	701(30.6)	620(61.2)	
Middle school	5481(19.5)	359(15.7)	99(9.8)	
High school or above	2416(8.6)	786(34.4)	26(2.5)	
employment; n(%)				
employed	18482(65.9)	1802(78.8)	832(82.1)	< 0.001
retired	3793(13.5)	12(0.5)	16(1.6)	
Other	5775(20.6)	474(20.7)	165(16.3)	
Per capital Household income; n(%)				

HP: hypertension; PM_{2.5}: particulate matter with an aerodynamic diameter ≤ 2.5 μm; BMI: body mass
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Variables	Han (n = 28050)	Tibetan (n = 2288)	Yi (n = 1013)	Pvalue
Q1	4498(16.0)	861(37.6)	357(35.1)	< 0.001
Q2	5017(17.9)	758(33.1)	228(22.5)	
Q3	5609(20.0)	407(17.8)	179(17.7)	
Q4	6051(21.6)	189(8.3)	169(16.7)	
Q5	6865(24.5)	73(3.2)	81(8.0)	
missing	10(-)	-	-	
BMI; n(%)				
Underweight	2827(10.1)	149(6.5)	192(19.0)	< 0.001
Normal weight	16584(59.1)	1376(60.2)	652(64.4)	
Overweight	7019(25.0)	632(27.6)	132(13.0)	
Obese	1620(5.8)	130(5.7)	37(3.6)	
missing	-	1(-)	-	
Smoking; n(%)	7705(28.6)	353(15.7)	395(39.5)	< 0.001
Alcohol consumption; n(%)	7320(26.2)	225(10.0)	241(23.9)	< 0.001
Physical activity; n(%)	9448(33.7)	889(38.9)	141(13.9)	< 0.001
Health check; n(%)	13344(47.6)	1290(56.4)	366(36.1)	< 0.001
Brush teeth every day; n(%)	24433(87.1)	1457(63.7)	719(71.0)	< 0.001
anxiety/depression; n(%)				
not at all	23743(84.6)	2103(91.9)	914(90.2)	< 0.001
moderate	3918(14.0)	174(7.6)	93(9.2)	
severe	389(1.4)	11(0.5)	6(0.6)	
VAS; mean(s.d.)	72.8(17.3)	77.3(15.1)	73.4(14.4)	< 0.001

HP: hypertension; PM_{2.5}: particulate matter with an aerodynamic diameter ≤ 2.5 μm ; BMI: body mass

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Variables	Han (n = 28050)	Tibetan (n = 2288)	Yi (n = 1013)	Pvalue
comorbidity; n(%)	9563(34.1)	471(20.6)	246(24.3)	< 0.001
HP: hypertension; PM _{2.5} : particulate matter with an aerodynamic diameter ≤ 2.5 µm; BMI: body mass index.; VAS: visual analogue scale.				

Figure 3 Distribution of PM_{2.5} Concentrations for the Han, Yi and Tibetan People

Table 2 Comparison of Sociodemographic and Major Risk Factors by Ethnicity

Table 3 showed the results of associations between PM_{2.5} and hypertension. In crude model, higher PM_{2.5} concentration was associated with increasing risk of hypertension with a crude odds ratio (OR) of 1.11 (95% CI, 1.09–1.14) for a PM_{2.5} increment of 10 µg/m³. After fully adjusted for covariates (Model 4 in Table 3), the positive association remained statistically significant (OR: 1.08; 95% CI, 1.04–1.12). Results of the fully adjusted model was listed in Table S2.

Table 3
The Results of Logistic Regression Analysis of Hypertension, PM_{2.5} and Covariates for 2013 and 2018

Variables	β	S. E.	OR	95% CI
Crude Model	0.11	0.01	1.11	1.09 ~ 1.14
Model 1	0.05	0.02	1.06	1.02 ~ 1.09
Model 2	0.07	0.02	1.08	1.04 ~ 1.11
Model 3	0.06	0.02	1.06	1.02 ~ 1.10
Model 4	0.08	0.02	1.08	1.04 ~ 1.12
OR: odds ration; CI: confidence interval.				
Model 1: adjusted for age, sex and ethnicity;				
Model 2: model 1 + adjusted for BMI, comorbidity, anxiety/depression and VAS;				
Model 3: model 2 + adjusted for education and per capital household income;				
Model 4: model 3 + adjusted for per capital annual salt sales volume of each county/district.				

Table 3. The Results of Logistic Regression Analysis of Hypertension, PM_{2.5} and Covariates for 2013 and 2018

The results of stratified analyses were shown in Fig. 4. The ORs of hypertension with a 10 µg/m³ comorbid participants (OR: 1.18; 95% CI, 1.12–1.25) and Yi

minority group (OR: 1.75; 95% CI, 1.28–2.38). The associations between PM_{2.5} exposure and hypertension stratified by sex, age, BMI, ethnicity, and comorbidity were showed in Table S3.

Figure 4 The Results of Estimated ORs of Exposure to PM_{2.5} and Hypertension Based on Stratified Analysis

Based on the above analysis results, Yi minority people were exposed to lower PM_{2.5} concentrations (Han: 35.9 µg/m³, Yi: 11.9 µg/m³) but suffered a stronger adverse effect on hypertension (OR for Han: 1.08, OR for Yi: 1.75) when compared to Han people. To detect whether the differences between Han and Yi populations were attributed to their heterogeneous responses to PM_{2.5} exposure or other socioeconomic/environmental factors, corresponding analysis was conducted based on 4571 participants (including 3581 Han people and 990 Yi people) in Yi area. Positive association between PM_{2.5} exposure and hypertension persisted and the interaction term between PM_{2.5} exposure and Yi minority group was not statistically significant. The results were shown in Table 4.

Table 4
Estimated ORs of Exposure to PM_{2.5} and Hypertension in Yi Area

Variables	β	S. E.	P value	Odds ratio	95% CI
Crude model					
PM _{2.5}	0.77	0.06	< 0.001	2.17	1.93 ~ 2.43
Adjusted model ^a					
PM _{2.5}	0.35	0.07	< 0.001	1.42	1.23 ~ 1.65
Interaction term ^b	0.31	0.23	0.170	-	-
OR: odds ration; PM _{2.5} : particulate matter with an aerodynamic diameter ≤ 2.5 µm; CI: confidence interval.					
a: Adjusted for age, sex, ethnicity (Han and Yi), BMI, comorbidity, anxiety/depression, VAS, education, per capital household income, per capital annual salt sales volume of each county/district and interaction between PM _{2.5} and Yi minority group.					
b: Interaction between PM _{2.5} and Yi minority group					

Table 4 Estimated ORs of Exposure to PM_{2.5} and Hypertension in Yi Area

To further explore potential factors related to ethnic disparity, whether domestic fuel type had synergy effect on ambient PM_{2.5} exposure was tested using the data of 2013. Yi people were more likely to use unclean fuel type than their Han counterpart (76.1% versus 43.7%, *P*< 0.001) as shown in Table 5. The interaction term between ambient PM_{2.5} exposure and clean fuel type was not statistically significant. But

the addition of interaction term tremendously changed the coefficient of PM_{2.5} exposure. The results were showed in Table 6.

Table 5
Comparison of Domestic Fuel Type between Han and Yi Minority Group in 2013

Variables	Han	Yi	P value
Fuel type; n(%)			
unclean	6092(43.7)	404(76.1)	< 0.001
clean	7847(56.3)	127(23.9)	

Table 6
Estimated ORs of Exposure to PM_{2.5} and Hypertension after Adjustment of Domestic Fuel Type in 2013

Variables	β	S. E.	P value	Odds ratio	95% CI
Crude model					
PM _{2.5}	0.08	0.03	0.003	1.09	1.03 ~ 1.15
Model 1 ^a				-	-
PM _{2.5}	0.07	0.03	0.022	1.07	1.01 ~ 1.13
Model 2 ^b					
PM _{2.5}	0.14	0.05	0.005	1.15	1.04 ~ 1.27
Interaction term ^c	-0.10	0.05	0.063		
OR: odds ration; PM _{2.5} : particulate matter with an aerodynamic diameter $\leq 2.5 \mu\text{m}$; CI: confidence interval.					
a: Adjusted for age, sex, ethnicity, BMI, comorbidity, anxiety/depression, VAS, education, per capital household income per capital annual salt sales volume of each county/district and domestic fuel type.					
b: Adjusted for age, sex, ethnicity, BMI, comorbidity, anxiety/depression, VAS, education, per capital household income, per capital annual salt sales volume of each county/district, domestic fuel type and interaction between PM _{2.5} and domestic fuel type					
c: Interaction between PM _{2.5} and clean domestic fuel					

Table 5 Comparison of Domestic Fuel Type between Han and Yi Minority Group in 2013

Table 6 Estimated ORs of PM_{2.5} Exposure and Hypertension after Adjustment of Domestic Fuel Type in 2013

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Sensitivity analyses generated similar results that increasing PM_{2.5}-concentration exposure was related to higher risk of hypertension. The results of sensitivity analyses were shown in Table S4.

Discussion

As it is acknowledged, in China, differences in health effects of long-term air pollution exposure among subgroups defined by race/ethnicity have not been examined, nor have potential synergies of ethnicity clustered social, psychosocial and environmental factors been disentangled. This is the first study to examine the different effects of long-term exposure of PM_{2.5} and prevalence of hypertension among Han, Tibetan and Yi population in China. It is found that higher long-term exposure of PM_{2.5} was associated with increased risk of hypertension in multi-ethnic population. Comorbidity and ethnicity would modify the effect of long-term PM_{2.5} exposure on prevalence of hypertension. Comorbidity would intensify the effect. Compared with Han population, the association is stronger in Yi population.

This study focuses on the relationship between long-term exposure of PM_{2.5} and prevalence of hypertension. Five-year average PM_{2.5} concentrations are used to measure the long-term exposure because the NHSS is conducted every five years. Hypertension is a chronic disease caused by long-term effects of environmental and genetic factors. Sensitivity analyses obtain similar results when using different exposure windows, which is consistent with the findings of Lin et al ⁶. Effects of short-term exposure on blood pressure is minor and can be easily reversed as the exposure is removed ³⁷. Additionally, there also exist many other factors that can sway blood pressure. Therefore, hypertension is more stable, and the effects of exposure is relatively certain.

The possible biological mechanism how PM_{2.5} exposure affects hypertension involves systemic inflammation, oxidative responses ^{38,39}. PM_{2.5} could elicit systemic oxidative stress and inflammation, thus increasing circulation of activated immune cells and inflammatory cytokines. Consequently, vascular endothelial dysfunction could lead to an imbalance in vascular homeostatic responses ⁴⁰. PM_{2.5} also affects blood pressure by altering autonomic nervous system balance and activating hypothalamus-pituitary-adrenal axis ^{38,41}.

Positive associations between the long-term exposure of PM_{2.5} and hypertension are inconsistent from existing epidemiologic studies. In this study, positive associations are obtained, which is consistent with several previous studies. A Canadian population-based cohort demonstrated a 3% increase of incident hypertension associated with 2.1 µg/m³ increase in PM_{2.5} ⁸. An observational study of older Americans found that 3.91 µg/m³ increase in PM_{2.5} was strongly associated with increased prevalence of hypertension with POR of 1.24 ⁹. A China PAR cohort study reported that a PM_{2.5} concentration increment of 10 µg/m³ could increase 11% risk of hypertension ¹⁰. Another Chinese cross-sectional study among older adults reported that OR of hypertension was 1.14 with PM_{2.5} concentration increments of 10 µg/m³ ⁶. A Chinese nationwide cross-sectional study of middle-aged and elderly people reported a weaker

association that 41.7 $\mu\text{g}/\text{m}^3$ increase in $\text{PM}_{2.5}$ was associated with higher prevalence of hypertension with OR of 1.11⁷. However, American Multi-Ethnic cohort study found no association between long-term exposure $\text{PM}_{2.5}$ and blood pressure¹². And a recent Chinese cross-sectional study also found the association non-significant¹³. The inconsistency may be partially illustrated by heterogeneity of study design, study setting, constituents of particle matter, exposure assessment, population characteristics, and covariates included in models²⁷.

Ethnicity shows complicated modification effect on the association between long-term $\text{PM}_{2.5}$ exposure and hypertension. The association in the Tibetan group is negative, which is mostly due to its low exposure level, very close to the lower bound of theoretical threshold of ambient $\text{PM}_{2.5}$ concentration (2.4 ~ 5.9 $\mu\text{g}/\text{m}^3$)². Meanwhile, the Tibetans are reported to be of high hypertension prevalence²⁴. High salt diet, high altitude residence, and related genetic adaptation are recognized as major risks^{24, 42–44} which may outweigh the effect of air pollution.

Stronger association is observed in Yi population. Analysis in Yi area showed that the interaction of $\text{PM}_{2.5}$ exposure and ethnicity was no longer statistically significant, indicating that the ethnic differences are mainly caused by socioeconomic and environmental factors. Although the average age of Yi participants tends to be younger than the Han, their education attainment and income level are likely to be lower than Han people. Compared with Han people, Yi minority people are less likely to have symptoms of anxiety/depression and comorbidity. Meanwhile, health-related behaviors of Yi minority people are poorer than Han counterpart. Yi people are more likely to smoke and less likely to do physical activities and to brush their teeth every day. Except the individual factors, the Yi area is less developed than Han area both in economy and healthcare services³³. Findings in this study are consistent with a few studies^{15, 45}. Erqou et al. found a 45% higher risk of cardiovascular events among blacks when compared to whites, which was partly because of black people's higher chronic exposure to $\text{PM}_{2.5}$. However, the association between cardiovascular events and race was no longer statistically significant after further adjustments for measures of SES (i.e., income and education)⁴⁵. Hicken et al. reported that racial/ethnic differences could be partly adjusted by markers of socioeconomic, psychosocial and environmental factors¹⁵.

Existing studies suggested that unclean domestic fuel could enhance the health risk of $\text{PM}_{2.5}$ exposure^{7, 46}. Over 76% of Yi people uses solid fuel to cook, including coal and forestry biomass in 2013. The proportion was dramatically higher than that of the Han people. Exposure to household air pollution from indoor unclean fuel is an important environmental health problem in low and middle-income countries⁴⁷. Previous studies found that unclean household fuel usage would elevate women's blood pressure^{48, 49}. Studies based on Indian cohort indicated that indoor solid fuel would enhance the effect of $\text{PM}_{2.5}$ exposure on insulin resistance⁴⁶, but the enhanced effect was not significant on SBP elevation due to insufficient statistical power⁵⁰. In another nationwide cross-sectional study in China, stronger associations between higher levels of ambient $\text{PM}_{2.5}$ and higher SBP were observed in participants who

Loading [MathJax]/jax/output/CommonHTML/jax.js ification effect was not significant on hypertension⁷. In this

study, with 2018 data not collected, only data of domestic fuel from 2013 was used to test the modification effect of fuel type. It is insufficient to test the interaction of $PM_{2.5}$ exposure and domestic fuel type for the hypertension prevalence in Yi minority group. Even though the interaction of $PM_{2.5}$ exposure and domestic fuel type is not significant, unclean fuel type would greatly increase the OR of $PM_{2.5}$ exposure. The disproportionate distribution of unclean fuel by ethnicity would be an important cause of ethnic disparity. Recently, Chinese government is committed to health poverty alleviation⁵¹. As an universal access to clean energy for household can contribute to Sustainable Development Goals (SDGs) for health and energy, measures should be taken to the promote the usage of clean household fuel⁵².

Other chronic diseases would enhance the effect of long-term $PM_{2.5}$ exposure on hypertension. There are studies with the findings that participants with chronic diseases like hypertension and diabetes are more susceptible to long-term $PM_{2.5}$ exposure^{20, 53, 54}. Besides, patients' pre-existing coronary heart diseases, chronic lung diseases, or heart failure were also recognized as susceptible population⁵⁵. Age and BMI were also found possible to modify the effect of long-term $PM_{2.5}$ exposure^{6, 7}. In this study, stronger associations are found in the elderly (aged 60 and above), but the interaction term is non-significant. Besides, modification effect of BMI is not observed, which may be the result of that BMIs of participants are relatively low with a mean of 22.5 kg/m². This finding is similar to that of another study¹³.

This study has several strengths. It is based on representative large survey data of Sichuan Province with ethnically diverse population. Additionally, individual information is collected including specific individual ethnicity, which makes it possible to adjust wide range of possible covariates and capture susceptibility. And high-resolution satellite-based approach allows allocating individual exposure of ambient $PM_{2.5}$ precisely.

Despite of those strengths, this study also has several limitations. First, its data come from cross-sectional surveys, which makes it hard to inference causal relationship between the long-term exposure $PM_{2.5}$ and hypertension. Second, the surveys lacks dietary information which is an important modifier of the associations between long-term exposure of $PM_{2.5}$ and hypertension. Third, self-reported physician-diagnosed hypertension is used to define whether participants are with hypertension rather than blood pressure measurements.

Conclusion

This study provides evidence that long-term exposure to $PM_{2.5}$ is associated with higher risk of hypertension from an ethnically diverse population. A stronger association is noticed in Yi minority people. The effect differences among multi-ethnic people are mainly due to socioeconomic and environmental factors, of which unclean domestic fuel type is an important contributor.

CI, confidence interval; OR, odds ratio; PM_{2.5}, particulate matter with an aerodynamic diameter $\leq 2.5 \mu\text{m}$; SBP, systolic blood pressure; DALYs, disability adjusted of life years; HSS, health service survey; NHSS, national health service survey; HP, hypertension; BMI: body mass index.; VAS:visual analogue scale.

Declarations

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Authorship contribution statement

Jiayue Xu, Minghong Yao and Gonghua Wu participated the sixth National Health Service Survey in Sichuan Province, conducted data analysis and drafted the first-version draft. Yuqin Zhang simulated the PM_{2.5} concentration in 2017. Zhanqi Duan, Xing Zhao and Juying Zhang contributed to analysis and design and provided important comments while developing the manuscript. Jiayue Xu is substantively responsible to revise manuscript. The author(s) read and approved the final manuscript.

Ethics approval and consent to participate

The NHSS is a national survey organized by the National Health and Family Planning Commission of China. The 2013 and 2018 National Health Services Surveys were all legal surveys approved and kept a record by the National Statistical Bureau. Oral consent of participate was obtained before the household survey.

Consent for publication

Not applicable

Conflicts of Interest

The authors declare that they have no conflicts of interests.

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Figures

Fig.4 The results of estimated ORs of exposure to PM_{2.5} and hypertension based on stratified analysis

Figure 1

The Results of Estimated ORs of Exposure to PM_{2.5} and Hypertension Based on Stratified Analysis

Fig.3 Distribution of PM_{2.5} concentrations for the Han, Yi and Tibetan people

Figure 2

Distribution of PM2.5 Concentrations for the Han, Yi and Tibetan People

Figure 3

The PM_{2.5} Concentration and Prevalence of Sample Districts/Counties. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Fig.1 The distribution of $PM_{2.5}$ concentration

Figure 4

The Distribution of $PM_{2.5}$ Concentration

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