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ABSTRACT
Hypertension is currently one of the most common chronic diseases with high global prevalence associated with a huge social and economic burden. In recent years, air pollution has become a focus of research, especially the effects of PM2.5 on hypertension. However, few studies have considered the spatial properties of the sample; thus, the results might be unreliable. Based on the China Health and Retirement Longitudinal Study (CHARLS) and the Environmental Status Bulletin for each province in China, we used the extended shared component model (SCM) to fit the spatial variation of hypertension risk and to reveal the impact of PM2.5 on hypertension in males and females. Our results revealed that the crude prevalence of hypertension for the whole population in China was 32.74% in 2015, with the prevalence in men experiencing slightly higher than that in women (32.92% vs. 32.58%). We found that the distribution of hypertension prevalence exhibited obvious spatial aggregation for the whole population in China (Moran's I = 0.39, P = 0.001), with similar results in both men (Moran's I = 0.18, P = 0.027) and women (Moran's I = 0.52, P = 0.001). Furthermore, the smoothed results obtained using the SCM indicated that some eastern and central provinces had relatively higher hypertension risk, while the risk in southeastern provinces was much lower. The risk was also relatively lower in most western provinces, except for some northwestern regions. Notably, our results showed that PM2.5 was a risk factor for hypertension, and the impact of PM2.5 on women was slightly greater than that on men, with odds ratios (OR) of 1.063 (1.041, 1.086) and 1.048 (1.025, 1.071), respectively. Our findings suggest the existence of distinct spatial differences in the prevalence of hypertension and small sex-related differences in the risk of hypertension in China.

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Spatial analysis; PM2.5; hypertension; shared component model (SCM)

Introduction

Hypertension is one of the most common chronic disease worldwide, nearly 17 million deaths due to cardiovascular diseases and 9.4 million deaths due to complications of hypertension reported by the World Health Organization (WHO) in 2013. As a middle-income country, the prevalence of hypertension in China is equally high. According to the National Nutrition and Chronic Diseases Status Reports, the prevalence of hypertension in adults aged 18 and over was 27.9% in 2015, remaining at a high level in subsequent years. In addition, the prevalence of hypertension also increases with age (Shengshou and Runlin et al. 2019). Thus, hypertension represents a heavy social and economic

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burden (Zhou et al. 2019). With the deterioration of organs and body functions, the middle-aged and elderly individuals represent are vulnerable to chronic diseases, especially high blood pressure. Thus, in the absence of effective prevention and control strategies, the prevalence of hypertension will continue to rise in the next few decades with the rapid increase in the aging population.

There are many reports on the risk factors of hypertension, although the results are complicated. Many studies have shown that individual behavior, family history, genetic factors and lifestyle are all related to the occurrence of hypertension (Yong and Yun et al. 2010; Wheaton et al. 2012; Xia and Hua 2012). In addition, dyslipidemia, diabetes and hyperuricemia are also risk factors for hypertension (Howard et al. 2010; Soltani et al. 2013). However, it cannot be overlooked that approximately 70% of the changes in an individual's blood pressure are influenced by environmental factors and the interactions between the environment and genes (Bochud and Guessous, 2012). Since 1990, many epidemiological studies have investigated the relationship between hypertension and air pollutants such as carbon monoxide (CO), nitrogen oxides (NO_x) and ozone (O_3). Based on cohort data, Tao et al. found that O_3 and NO_2 significantly increased the risk of cardiovascular diseases such as hypertension (Tao et al. 2012). Recently, inhalable particulate matter has become the most prominent environmental pollution problem worldwide, especially in China. Therefore, studies have increasingly been focused on the effects of inhalable particulate matter on hypertension. Many epidemiological studies have shown that long-term exposure to inhalable particulate matter significantly increase the incidence of cardiovascular disease and even death. Researchers such as Chuang et al. found that PM2.5 was significantly associated with high blood pressure in Taiwan (Chuang et al., 2010). Furthermore, Cai et al. quantified the effects of PM2.5 on hypertension (Cai et al. 2016). However, none of these studies considered the spatial autocorrelation or spatial heterogeneity of PM2.5; therefore, the results may be not completely reliable.

With the advantages of flexibility and simplicity, spatial methods based on the Bayesian hierarchical model (BHM) have become a hot topic in disease research. Furthermore, with the development of the Markov chain Monte Carlo (MCMC) method, multiple methods have been derived from the BHM, including the shared component model (SCM) which is an advancement of the BHM. The SCM is based on the concept of the existence of common risk factors among diseases, such that the potential risk can be further decomposed into common and specific risk. The basic assumption of this model is that there is a certain correlation between various diseases; that is, the risks between diseases have common influencing factors and the effects of these factors vary greatly between different regions. The common and specific components of the model are independent of each other, and the parameters of the model are uncertain, so the prior distribution must be set in advance. In addition, SCM is based on the BHM framework and uses full Bayesian methods for risk estimation. Therefore, the model has higher research value due to its flexibility and extensibility. For example, the types of diseases included in the model can be expanded from two to multiple, and the common components can also be expanded; thus, the model can provide more in-depth information for spatial epidemiological analysis. At present, The SCM is widely used to analyze sex differences in disease risk, sparse data for small regions, the existence of covariates, disease risk estimation from multiple data sources, estimation of missing data and disability-adjusted life years (DALY) in a small area (Earnest et al. 2010; MacNab 2010; Onicescu et al. 2010; Ancelet and Abellan et al. 2012; Held et al. 2016).

Therefore, we used the SCM to explore the spatial distribution of hypertension risk in middle-aged and elderly people in China in our study. Simultaneously, the impact of PM2.5 on the occurrence of hypertension was explored and sex differences were further investigated.

Materials and methods

Data

We obtained data from the China Health and Retirement Longitudinal Survey (CHARLS). CHARLS was designed to collect high-quality microscopic data representing individuals aged 45 years and older to explore the aging problem in China. The response rate and data quality are among the highest of similar surveys in the world, and have therefore been widely used and recognized in academia. We selected the most recently published data in 2015 from CHALRS to study the hypertension prevalence in the middle-aged and elderly people in China. In addition, we obtained the average daily concentrations of PM2.5 for 31 provinces in 2015 in China through the Environmental Status Bulletin for each province. Blood pressure was measured by professional doctors using a standard mercury sphygmomanometer; blood pressure values were based on the mean of three repeated measurements. People with hypertension were defined as having a systolic blood pressure ≥140 mmHg, a diastolic pressure ≥90 mmHg, or those currently using anti-hypertensive drugs.

Statistical methods

Descriptive analysis

The prevalence of hypertension in Ningxia, Tibet and Hainan Provinces was determined using the CHALRS database of 28 provinces surveyed in 2015. First, we conducted disease mapping to describe the spatial distribution of the prevalence of hypertension in China. Spatial mapping of PM2.5 was also conducted to study the impact of PM2.5 on hypertension.

Spatial autocorrelation analysis

Spatial autocorrelation analysis is performed to evaluate the relationship of a variable between one region and its surroundings. This process allows quantitative exploration of the types of correlation, high-aggregation regions and spatial distribution characteristics over time, which provides insights into the risk factors in specific regions. Here, we present a preliminary understanding the potential existence of spatial aggregation in the prevalence of hypertension, and Moran's I values was calculated to measure spatial autocorrelation according to the following formula:

$$I = \frac{n\Sigma_{i=1}^{n}\Sigma_{i=1}^{n}wij(xi-\bar{x})(xj-\bar{x})}{\Sigma_{i=1}^{n}\Sigma_{i=1}^{n}wij\Sigma_{i=1}^{n}(xi-\bar{x})^2}$$

where n denotes the number of spatial regions; x_i and x_j represent the observed values of the variables at the spatial positions i and j; $\bar{x}$ represents the average of all observations in all regions; and w_{ij} is the spatial weight calculated as follows:

$$w_{ij} = \begin{cases} 1, When\ two\ areas\ are\ close\ to\ each\ other \\ 0, Others \end{cases}$$

Shared component model (SCM)

The SCM was used to study the effects of PM2.5 on hypertension between the sexes. The results were mapped to explore the spatial distribution characteristics of the hypertension risk. The SCM model can be written as follows:

$$\begin{aligned}
&O_{ji} \sim bin(p_{ji}, n_{ji}) \\
&\log it(p_{ji}) = \alpha_j + \beta_j x_{ji} + eta_{ji} \\
&eta1_i = \varphi_i * \delta + v1_i \\
&eta2_i = \frac{\varphi i}{\delta} + v2i \\
&\eta1 = var(\varphi_i{}^*\delta)/(var(\varphi_i{}^*\delta) + var(v1_i)) \\
&\eta2 = var(\varphi_i/\delta)/(var(\varphi i/\delta) + var(v_2 i))
\end{aligned}$$

Here, i denotes all the regions; j denotes the sex (1 for men, 2 for women); O_i represents the actual number of patients in each region; n_i denotes the total population of each region; and p_i is the potential prevalence of the area. φi is the shared random variation for men and women, and δ and 1/δ represent the weight of the shared variation of men and women, respectively. η_j represents the proportion of the shared component contributing to the random effect, and v_{ji} denotes the specific random variation.

It should be emphasized that δ and 1/δ satisfy the condition that the sum of their logarithm equals 0, ensuring that the model could be identified. Furthermore, the shared and specific components can be decomposed as follows:

$$\varphi i = ush_i + ssh_i$$
$$v_{ji} = bind_{ji} + bspat_{ji}$$

Here, *ush* and *bind* denote spatially unstructured random effects, while *ssh* and *bspat* represent spatially structured random effects. To describe the results more precisely, we calculated the odds ratio (OR) according to the following formula:

$$\exp(etai) = \left(\frac{p_i}{1 - p_i}\right) \Big/ \exp(\alpha)$$

Here, α represents the baseline risk, and $\exp(eta_i)$ represents the OR for each region compared to the baseline risk. Furthermore, we calculated index γ, which represents the proportion of the spatial structured random effects, according to the following formula:

$$\gamma = var(s[i])/(var(s[i]) + var(u[i])$$

Values of $\gamma > 50\%$ indicates that the spatial structured effect is dominant, revealing the existence of strong spatial clustering. Otherwise, it shows that the variation is mainly derived from spatial heterogeneity.

We used the MCMC Simulation method to achieve Bayesian inference for the SCM. To make the results reliable and easy to compare, we selected two independent Markov chains, each with 5,000 pre-iterations, followed by 50,000 iterations and adjusted the number of pre-iterations according to convergence conditions. The convergence was diagnosed by the classic variance ratio method, combined with dynamic trajectory maps and autocorrelation figures (ACF). According to Sinharay (Sinharay and Stern 2003) et al., MCMC algorithm convergence occurs when the different chains combined in dynamic trajectory maps and there was no correlation between parameters for ACF. After the model reached convergence, we used the deviation information criterion (DIC) to evaluate and select the ideal model.

Software

Data extraction, management and descriptive analysis were performed using SAS (version 9.4). The SCM was built using R calling OpenBugs3.2.2. All weight matrices were created using GeoBUGS. All maps were generated using GeoDa1.8.16.4.

Results

Statistical descriptions

Overall status of hypertension prevalence

In total, 20,927 were included in our study after excluding missing data. Of the total population, men accounted for 47.45%, and women accounted for 52.55%. The total prevalence of hypertension was 32.74%, with a slightly higher prevalence in men (32.92% versus (vs.) 32.58%). The perspective of the whole population is shown in Figure 1(a). The hypertension prevalence in the northeastern region (three provinces) was relatively high, especially in Heilongjiang Province (43.41%). The hypertension prevalence in the eastern region (10 provinces) was also high, with the highest prevalence in Shandong province (40.17%). The prevalence in the southeastern coastal provinces was generally low, especially in Fujian, where the prevalence rate was the lowest in China at only 23.46%. The hypertension prevalence in the central region (six provinces) was generally low. The prevalence in the western region (12 provinces) was also lower than that in the northeast, while the prevalence in Qinghai in the northwest was higher, reaching 40.35%. Furthermore, as shown in Figure 1(b), the spatial distribution of the prevalence in men was similar to that of the whole population. The regions with the highest hypertension prevalence were concentrated mainly in the northeastern region, as well as some eastern and northwestern provinces, such as Heilongjiang (49.72%), Shandong (41.71%) and Qinghai (42.11%) Provinces. The prevalence in the rest of the provinces was relatively low, fluctuating between 20.73% and 39.60%. Among them, the prevalence of hypertension in the southeastern coastal provinces and some central provinces was very low. For example, the prevalence in Hubei, Sichuan and Shaanxi was 27.67%, 29.53% and 29.86%, respectively, and Fujian had the lowest prevalence in China (20.73%). Figure 1(c) shows that the prevalence in women was slightly lower than that in men. Specifically, the prevalence in the northeastern region (Heilongjiang), some central provinces (Anhui and Henan) and some eastern provinces (Hebei and Shandong) as well as Qinghai province was quite high, with the highest in Hebei Province (42.32%).). In contrast, the prevalence among women was much lower in other provinces, such as the southeastern provinces (Fujian, Guangdong) and some central provinces (Hubei, Hunan, Jiangxi, Chongqing, and Guangxi) and western provinces (Gansu). The prevalence in all these provinces was lower than 29.00%, with the prevalence in Guangdong being the lowest in China for women (25.17%).

We also conducted a global spatial autocorrelation analysis of the distribution of hypertension prevalence. Moran's I values were used to determine the existence of global spatial aggregation.

As shown in Table 1, the spatial aggregation of the overall prevalence of hypertension was statistically significant, with a Moran's I value of 0.39 (P = 0.001).

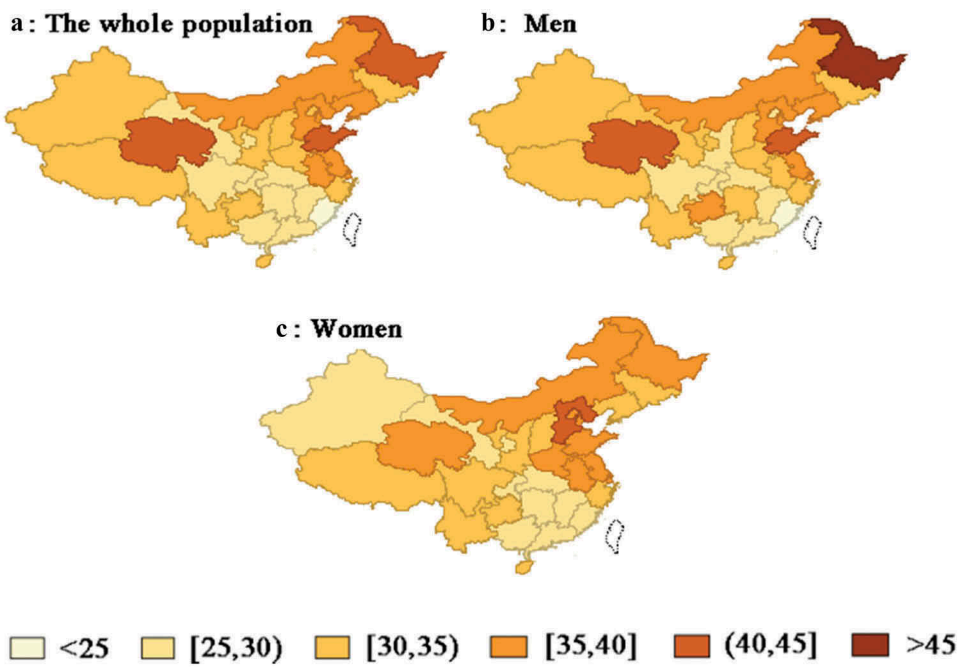

Figure 1. The prevalence of hypertension in China in 2015.

Table 1. Moran's I values for hypertension prevalence in China in 2015.

	Moran's *I*	*P*-value
Total	0.39	0.001
Men	0.18	0.027
Women	0.52	0.001

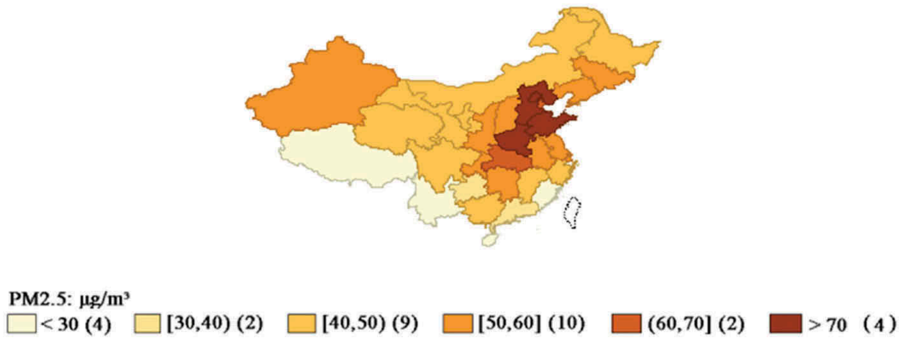

Figure 2. The distribution of PM2.5 concentration in China in 2015.

Global spatial aggregation analysis for both men and women yielded Moran's I values of 0.18 ($P = 0.027$) and 0.52 ($P = 0.001$), respectively, indicating a need for spatial research.

The distribution characteristics of PM2.5 in China

According to the Environmental Status Bulletin for each province in 2015, the daily average PM2.5 concentration ranged from 13 μg/m^3 to 86 μg/m^3 among the provinces investigated. Furthermore, we performed spatial mapping to reveal the characteristics of PM2.5 distribution. As shown in Figure 2, the regions with the highest concentration were located mainly in eastern provinces (Beijing, Hebei, and Shandong) and some central provinces (e.g. Henan, and Hubei), with the concentration in Henan Province reaching 86.00 μg/m^3. The PM2.5 pollution in Jilin, Liaoning and Xinjiang Provinces was also very serious (≥53 μg/m^3). Light pollution was reported in the remaining provinces, especially in Fujian, Yunnan and Tibet (<30.00 μg/m3), with Fujian found to be the least polluted province in China (13.30 μg/m^3).

Sex differences in hypertension risk

Important parameters and evaluation of the model

First, we established Model 1 without the PM2.5 as a variable, before it was added into Model 2, and the MCMC method was used to estimate the parameters. The important parameters in the SCM are shown in Table 2.

From the perspective of fitting effects, the DIC only increased slightly and the pD decreased significantly after adding PM2.5. Furthermore, $\eta 1$ and $\eta 2$ were 0.949 and 0.945, respectively, in Model 1, suggesting that the unobserved common risk factors determined 94.9% and 94.5% of hypertension prevalence variations for men and women, respectively. After adding PM2.5, the proportion of shared components decreased significantly (men: 0.521, women: 0.505), suggesting that PM2.5 was an important risk factor for both men and women. The posterior median of the shared component weight δ was 1.018, indicating that the unobserved common risk factors affected men slightly more than women.

Table 2. Important parameters of the SCM.

	Model 1		Model 2	
Parameters	Men	Women	Men	Women
OR_PM2.5	–	–	1.048(1.025,1.071)	1.063(1.041,1.086)
η	0.949(0.708,0.989)	0.945(0.701,0.988)	0.521(0.159,0.876)	0.504(0.148,0.861)
δ	1.043(0.857,1.274)		1.018(0.460,2.298)	
DIC(pD)	444.500(18.180)		569.400(4.325)	

Furthermore, the OR was 1.048 for men and 1.063 for women in Model 2, implicating PM2.5 as a risk factor for hypertension in both men and women. Furthermore, the impact of PM2.5 on women was slightly greater than that on men.

The results of spatial smoothing of crude prevalence for the different sexes

As described in section *3.1.1*, we generated spatial maps to show the distribution characteristics of crude hypertension prevalence for men and women. However, this process did not take into consideration the interaction among neighboring regions, and so did not fully reveal the spatial distribution characteristics of hypertension prevalence. Therefore, we used the SCM to achieve spatial smoothing of the crude hypertension risk for men (Figure 3(a)) and women (Figure 3(b)).

As shown in Figure 3(a), Heilongjiang Province (OR = 1.52) in the northeast, Hebei and Tianjin Provinces (OR = 1.26, OR = 1.25, respectively) in the east, and Inner Mongolia (OR = 1.23) in the west had high risk of hypertension in men. The risks in Liaoning, Jiangsu, and Qinghai Provinces were also relatively high (OR >1.12). The risks of hypertension in the remaining provinces were relatively lower, especially in some northeastern and central provinces, such as Jiangxi, Fujian, and Guangdong (all OR <0.80). As shown in Figure 3(b), the distribution characteristics for hypertension in women were similar to those in men. The regions with the highest prevalence were mainly located in Heilongjiang, Hebei, and Shandong Provinces (OR >1.26). Some Provinces in the eastern (Jiangsu), central (Anhui) and northwest (Qinghai) regions also showed high risk (OR ≥1.10). The risks in other provinces were relatively lower, ranging from 0.70 to 1.19.

Thus, the prevalence of hypertension in men was slightly higher than that in women after spatial smoothing in the SCM. However, from the perspective of spatial distribution, the prevalence of hypertension in men and women was similar.

The results of spatial smoothing of hypertension risk related to PM2.5 for the different sexesgenders

To facilitate an intuitive understanding of the differences in the impact of PM2.5 on the risk of hypertension in men and women, we conducted spatial mapping of the SCM results. As shown in Figure 4, the spatial distribution of hypertension risk in men was slightly lower than that in women,

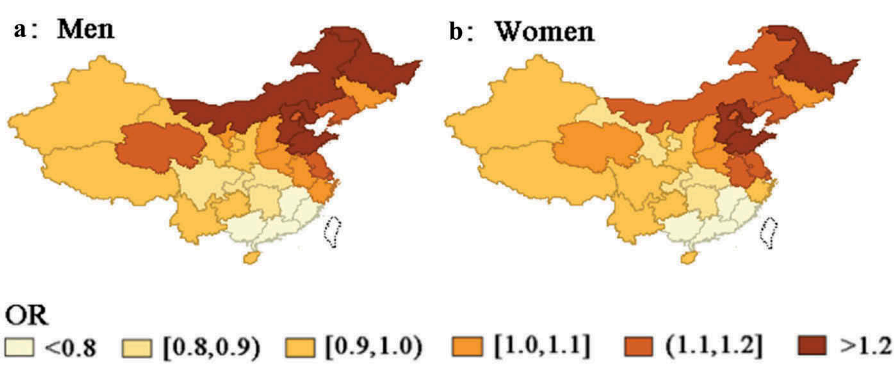

Figure 3. The results of spatial smoothing of hypertension prevalence in China in 2015.

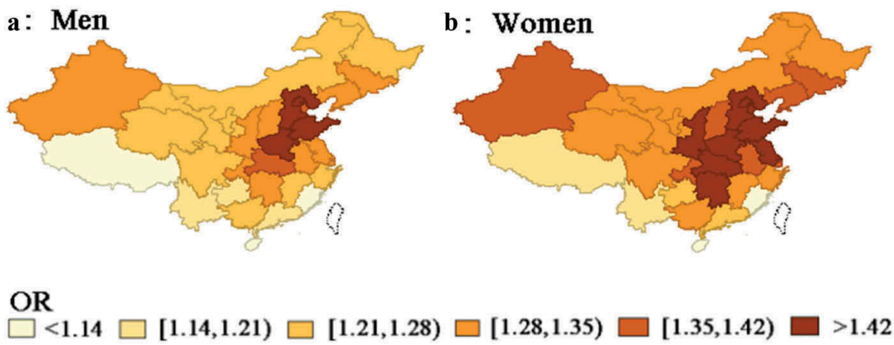

Figure 4. The risk of hypertension related to PM2.5 in 2015 of China.

suggesting that the impact of PM2.5 on hypertension was relatively higher for women. For men, the most seriously affected areas were located mainly in the eastern (Hebei, Beijing, and Shandong) and some central provinces (e.g. Henan, Hubei), with ORs >1.24, especially in Henan (1.50). In addition, the risks in northeastern (Jilin, Liaoning) and northwestern (Xinjiang) provinces were also relatively high (OR = 1.29, OR = 1.29, and OR = 1.28, respectively). The risks in other regions were relatively low, especially in Fujian and Tibet (OR = 1.06 and OR = 1.13, respectively). For women, the areas with high risk were located mainly in some eastern provinces, such as Hebei, Beijing, Tianjin, and Shandong (OR >1.53), and some central provinces, such as Shaanxi, Henan, Hubei and Hunan (OR >1.44). The risk of Xinjiang in the northwest was also noteworthy (OR = 1.38). The risks in other areas were relatively low, with the risk in Fujian provinces found to be the lowest in China (OR = 1.09)

Overall, our findings demonstrated that the impact of PM2.5 on hypertension was relatively greater for women than men in China. We also observed differences in the spatial distribution characteristics of hypertension risk for men and women.

Convergence and sensitivity analysis of the SCM

The convergence of OR for men and women are listed in Figure 5 based on the results of Model 2. According to the Brooks and Gelman statistics, all the key variables (MPSRF) tested fluctuated around 1. The two Markov chains showed good convergence, indicating that the model reached convergence and the estimation was relatively stable and reliable.

Furthermore, we performed sensitivity analysis on our model with three kinds of prioris, priori1: logdelta~dnorm (0.0, 8.0); priori2: logdelta~dnorm (0.0,10.5); and priori 3: delta~dunif (0.0, 0.08). The results of these models based on our settings are listed in Table 3.

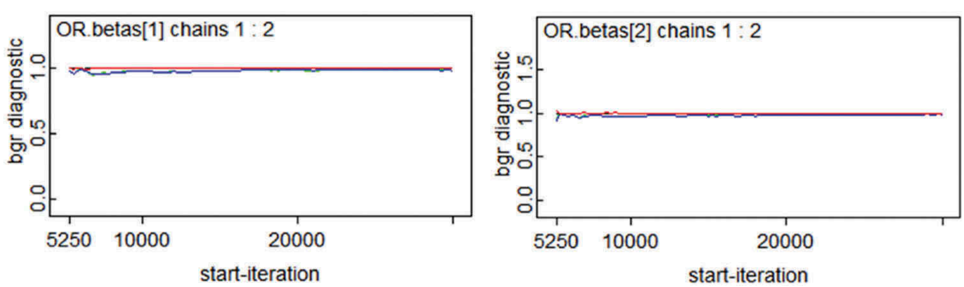

Figure 5. Convergence of some key parameters.

Table 3. The results of sensitivity analysis.

Parameters	Priori 1	Priori 2	Priori 3
OR_men	1.048 (1.025, 1.072)	1.048 (1.025, 1.072)	1.048 (1.025, 1.071)
OR_women	1.063 (1.041, 1.086)	1.063 (1.041, 1.086)	1.063 (1.041, 1.086)
η_men	0.521 (0.188, 0.846)	0.519 (0.190, 0.842)	0.531 (0.337, 0.718)
η_women	0.505 (0.175, 0.833)	0.505 (0.179, 0.828)	0.492 (0.303, 0.684)
δ	1.016 (0.516, 2.035)	1.013 (0.526, 1.989)	1.041 (1.002, 1.081)
DIC(pD)	569.000 (4.412)	569.900 (4.778)	570.400 (4.514)

In all three models, DIC and pD were close in terms of goodness-of-fit and there were no marked differences in the OR estimates. The differences in η and δ were almost identical at percentile level. In short, the key statistics and goodness-of-fit of the model were insensitive to different prioris.

Discussion

The spatial distribution of prevalence of hypertension

From the spatial distribution of crude prevalence of hypertension, the eastern regions, especially the northeast regions, and some northwestern provinces showed higher prevalence of hypertension among middle-aged and elderly people in China. It can be speculated that this phenomenon is related to the high obesity rates and alcohol consumption in these regions or the high daily salt intake in daily revealed in previous studies(Sailesh and RC C 2009; He and MacGregor 2010). In contrast, the prevalence of hypertension was much lower in the central and southeastern provinces. Thus, our findings are consistent with those of previous studies conducted in China(Yin et al. 2016; Lu et al. 2017). Furthermore, the results of spatial smoothing of crude prevalence and distribution characteristics using the SCM were quite similar for men and women. Both showed that the risk of hypertension was higher in the north of China and much lower in the south. These results are similar to those reported previously(Chen X et al., 2014), indicating that some risk factors, such as smoking, lifestyle, age and obesity play an important role in the occurrence of hypertension (Xu et al. 2016).

Effects of PM2.5 on hypertension

Previous studies, such as that reported by Guo (Guo and Tong et al. 2010) focused mainly on the short-term effects of PM2.5 on hypertension. The samples in our study were obtained from the CHARLS, a follow-up study; therefore, the PM2.5 exposure of the population was stable and continuous due to their relatively stable living environment. Consequently, we were able to explore the relationship between long-term exposure to PM2.5 and hypertension risk.

Analysis using the SCM showed that the posterior median OR was 1.048 for men and 1.063 for women, suggesting that PM2.5 pollution increases the risk of hypertension. Specifically, the relationships between PM2.5 levels and hypertension identified in our study are consistent with those reported previously. The American Cancer Society Cancer Prevention Study (ACSCPS) showed that every 10 μg/m^3 increase in PM2.5 increases the mortality associated with hypertension by 20% (Pope et al. 2014). Another Canadian cohort study showed that PM2.5 levels were closely related to hypertension (Chen H et al., 2014). Similarly, in a cross-sectional study, Chen et al. (Chen et al. 2015) also found that PM2.5 pollution increased the risk of hypertension, with an OR for hypertension of 1.05, which is very similar to that found in our study. Furthermore, the relationship between PM2.5 and hypertension can also be explained in terms of physiology. The potential mechanism is based mainly on the indirect effects of PM2.5 on the regulation of systemic inflammatory and oxidative responses, leading to the excitation of sympathetic nerves and subsequent arterial reconstruction (Giorgini and Rubenfire et al. 2015). Oxidative responses might also accelerate the circulation of immune cells and inflammatory cytokines and induce endothelial dysfunction, resulting in imbalance of blood vessel homeostasis. If the process described occurred repeatedly, it would eventually increase the flow resistance of the vessel, leading to an increase in blood pressure (Fuks et al. 2011). In addition, PM2.5 would cause an imbalance in the nervous system that leads directly to vasoconstriction (Coogan et al. 2012). In addition, it has been proposed that PM2.5 reduces the daily sodium excretion, resulting in impaired blood pressure regulation during the night. Excessive sodium deposition would also cause renal dysfunction, which would also increase blood pressure (Tsai et al. 2012). In conclusion, PM2.5 is an important risk factor for hypertension with clear physiological mechanisms. Furthermore, our studies also showed the existence of differences in the risk of hypertension in men and women, which might be related to the specific chemical substances attached to PM2.5, exposure measurement methods and lifestyle (Cai et al. 2016).

Differences in the impact of PM2.5 on hypertension in men and women

The posterior median OR of men and women were 1.048 and 1.063, respectively, suggesting that the impact of PM2.5 on the risk of hypertension in women was greater than that in men; these findings are consistent with those of previous studies (Chen H, et al., 2014; Lin and Guo et al. 2017). Although the men and women included in this study lived in similar places, they may have had quite different lifestyles. Women tend to exercise frequently outside, resulting more opportunities for exposure to PM2.5. From another perspective, a far greater proportion of smokers were men, although it is possible that PM2.5 is more harmful to non-smokers, with a concomitant increase in the OR for women. Thus, the reasons for the differences in the risks of hypertension in men and women remain to be clarified.

In terms of the distribution of hypertension risk, the effects of PM2.5 were greater in some eastern and central provinces, but smaller in the southeastern provinces. In some central provinces, the risk of hypertension was high, as was the level of PM2.5 pollution of PM2.5 in these provinces. For example, the risk of hypertension was relatively high in Henan, Hebei, Beijing and Shandong Provinces. These findings revealed that air pollution is an extremely serious health hazard that should be addressed to improve air quality and promote health. In contrast, the risk of hypertension was much smaller in Fujian Province for both men and women, which could be related to the high air quality in this region. However, the prevalence of hypertension was quite low at baseline level in Fujian Province. Notably, the distribution of hypertension risk was not completely consistent with the distribution of PM2.5. For instance, PM2.5 was low in the northeast, while the hypertension risk was relatively high, suggesting that diet, obesity, lifestyle and other factors deserve attention.

In short, the validity of the SCM could be increased by the surrounding areas, making the estimation of risk more stable and reliable (Ye et al. 2018). Therefore, the results of our study have high value for the prevention of hypertension. Based on the consideration of spatial autocorrelation and spatial heterogeneity, our results also provide epidemiological evidence for further research from a spatial perspective. However, some limitations of our study should be noted. First, our analysis was conducted at the level of the province, which precludes the provision of more detailed spatial scale data in China. Second, the PM2.5 data was derived from the Environmental Status Bulletin for each province, so differences in the measurement methods cannot be ruled out. Third, the PM2.5 and hypertension data used in our study were both obtained in 2015, thus limiting causality inferences. Although it was impossible to obtain PM2.5 data for all provinces in China before 2015, due to the continuity of air quality in each province, we could also explain the relationship between PM2.5 and hypertension.

Conclusions

The spatial analysis revealed the existence of distinct spatial differences in the prevalence of hypertension in China. Furthermore, our study showed that PM2.5 is a risk factor for hypertension and there are sex-related differences in the spatial patterns of hypertension risk related to PM2.5; although, these differences are relatively small.

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Conflicts of Interest

The authors declare no conflict of interest.

References

Ancelet S, Abellan JJ, Vilas VDJR. 2012. Bayesian shared spatial-component models to combine and borrow strength acrosss parse disease surveillance sources. Biometrical J. 3:385–404.

Bochud M, Guessous I. 2012. Gene-environment interactions of selected pharmacogenes in arterial hypertension. Expert Rev Clin Pharmacol. 5:677–686. doi:10.1586/ecp.12.58.

Cai Y, Zhang B, Ke W, Feng B, Lin H, Xiao J, Zeng W, Li X, Tao J, Yang Z, et al. 2016. Associations of short-term and long-term exposure to ambient air pollutants with hypertensionnovelty and significance. HYPERTENSION. 68:62–70. doi:10.1161/HYPERTENSIONAHA.116.07218.

Chen H, Burnett RT, Kwong JC, Villeneuve PJ, Goldberg MS, Brook RD, van Donkelaar A, Jerrett M, Martin RV, Kopp A, et al. 2014. Spatial association between ambient fine particulate matter and incident hypertension. CIRCULATION. 129:562–569. doi:10.1161/CIRCULATIONAHA.113.003532.

Chen S, Wu C, Lee J, Hoffmann B, Peters A, Brunekreef B, Chu D, Chan C. 2015. Associations between long-term air pollutant exposures and blood pressure in elderly residents of Taipei City: A cross-sectional study. Environ Health Perspect. 123:779–784. doi:10.1289/ehp.1408771.

Chen X, Wei W, Zou S, Wu X, Zhou B, Fu L, Wang H, Shi J. 2014. Trends in the prevalence of hypertension in Island and Coastal areas of china: a systematic review with meta-analysis. Am J Hypertens. 27:1503–1510. doi:10.1093/ajh/hpu026.

Chuang KJ, Yan YH, Chiu SY, Cheng TJ. 2010. Long-term air pollution exposure and risk factors for cardiovascular diseases among the elderly in Taiwan. Occupational and Environmental Medicine. 68:64–68.

Coogan PF, White LF, Jerrett M, Brook RD, Su JG, Seto E, Burnett R, Palmer JR, Rosenberg L. 2012. Air pollution and incidence of hypertension and diabetes in African American women living in Los Angeles. Ciculation. 6:767–772. doi:10.1161/CIRCULATIONAHA.111.052753.

Earnest A, Beard JR, Morgan G, Lincoln D, Summerhayes R, Donoghue D, Dunn T, Muscatello D, Mengersen K. 2010. Small area estimation of sparse disease counts using shared component models-application to birth defect registry data in New South Wales, Australia. Health Place. 16:684–693. doi:10.1016/j.healthplace.2010.02.006.

Fuks K, Moebus S, Hertel S. 2011. Long-term urban particulate air pollution, traffic noise, and arterial blood pressure. Environ Health Perspect. 12:1706–1711. doi:10.1289/ehp.1103564.

Giorgini P, Rubenfire M, Das R, Gracik T, Wang L, Morishita M, Bard R, Jackson EA, Fitzner CA, Ferri C. 2015. Particulate matter air pollution and ambient temperature. J Hypertens. 33:2032–2038. doi:10.1097/HJH.0000000000000663.

Guo YM, Tong SL, Li SS, Barnett AG, Yu WW, Zhang YS, Pan XC. 2010. Gaseous air pollution and emergency hospital visits for hypertension in Beijing, China: a time- stratified case-crossover study. Environ Health. 1:1–7.

He FJ, MacGregor GA. 2010. Reducing population salt intake worldwide: from evidence to implementation. Prog Cardiovasc Dis. 52:363–382. doi:10.1016/j.pcad.2009.12.006.

Held L, Graziano G, Frank C, Rue H. 2016. Joint spatial analysis of gastrointestinal infectious diseases. Stat Methods Med Res. 15:465–480. doi:10.1177/0962280206071642.

Howard BV, Comuzzie A, Devereux RB, Ebbesson SOE, Fabsitz RR, Howard WJ, Laston S, MacCluer JW, Silverman A, Umans JG, et al. 2010. Cardiovascular disease prevalence and its relation to risk factors in Alaska Eskimos. Nutrition, Metab Cardiovasc Dis. 20:350–358. doi:10.1016/j.numecd.2009.04.010.

Hu SS, Gao RL, Liu LS, Zhu ML, Wang W, Wang YJ, Wu ZS, Li HJ, Gu DF. 2019. China cardiovascular disease report 2018: summary. Chinese Cir J. 34:209–220.

Lin H, Guo Y, Zheng Y, Di Q, Liu T, Xiao J, Li X, Zeng W, Cummings-Vaughn LA, Howard SW, et al. 2017. Long-term effects of ambient PM2.5 on hypertension and blood pressure and attributable risk among older Chinese adults. HYPERTENSION. 69:806–812. doi:10.1161/HYPERTENSIONAHA.116.08839.

Lu J, Lu Y, Wang X, Li X, Linderman GC, Wu C, Cheng X, Mu L, Zhang H, Liu J, et al. 2017. Prevalence, awareness, treatment, and control of hypertension in China_ data from 1.7 million adults in a population-based screening study (China PEACE Million Persons Project). LANCET. 390:2549–2558. doi:10.1016/S0140-6736(17)32478-9.

MacNab YC. 2010. On Bayesian shared component disease mapping and ecological regression with errors in covariates. Stat Med. 29:1239–1249. doi:10.1002/sim.3875.

Onicescu G, Hill EG, Lawson AB, Korte JE, Gillespie MB. 2010. Joint disease mapping of cervical and male oropharyngeal cancer incidence in blacks and whites in South Carolina. Spat Spatiotemporal Epidemiol. 1:133–141. doi:10.1016/j.sste.2010.03.005.

Pope CA, Turner MC, Burnett RT, Jerrett M, Gapstur SM, Diver WR, Krewski D, Brook RD. 2014. Relationships between fine particulate air pollution, cardiometabolic disorders, and cardiovascular mortality. Circ Res. 116:108–115. doi:10.1161/CIRCRESAHA.116.305060.

Sailesh M, RC C N. 2009. Salt and high blood pressure. Clin Sci. 117:1–11. doi:10.1042/CS20080207.

Sinharay S, Stern H. 2003. Posterior predictive model checking in hierarchical models. J Stat Plan Inference. 1:209–221. doi:10.1016/S0378-3758(02)00303-8.

Soltani Z, Rasheed K, Kapusta DR, Reisin E. 2013. potential role of uric acid in metabolic syndrome, hypertension, kidney injury, and cardiovascular diseases: is It time for reappraisal?. Curr Hypertens Rep. 15:175–181. doi:10.1007/s11906-013-0344-5.

Tao Y, Huang W, Huang X, Zhong L, Lu S-E, Li Y, Dai L, Zhang Y, Zhu T. 2012. Estimated acute effects of ambient ozone and nitrogen dioxide on mortality in the pearl river delta of Southern China. Environ Health Perspect. 3:393–398. doi:10.1289/ehp.1103715.

Tsai DH, Riediker M, Wuerzner G, Maillard M, Marques-Vidal P, Paccaud F, Vollenweider P, Burnier M, Bochud M. 2012. Short-term increase in particulate matter blunts nocturnal blood pressure dipping and daytime urinary sodium excretion * Novelty and significance. HYPERTENSION. 60:1061–1069. doi:10.1161/HYPERTENSIONAHA.112.195370.

Wheaton AG, Perry GS, Chapman DP, Croft JB. 2012. Sleep disordered breathing and depression among U.S. adults: National health and nutrition examination survey, 2005-2008. SLEEP. 35:461–467. doi:10.5665/sleep.1724.

Xia Z, Hua LA. 2012. Study on the influence of hypertension knowledge and health belief on salt and cooking oil intake. Modern Preventive Medicine. 39:2679–2681.

Xu L, Lai D, Fang Y. 2016. Spatial analysis of gender variation in the prevalence of hypertension among the middle-aged and elderly population in Zhejiang Province, China. BMC Public Health. 16:1–12. doi:10.1186/s12889-016-3121-y.

Ye Z, Xu L, Zhou Z, Wu Y, Fang Y. 2018. Application of SCM with Bayesian B-Spline to spatio-temporal analysis of hypertension in China. Int J Environ Res Public Health. 15:1–18. doi:10.3390/ijerph15010055.

Yin M, Augustin B, Fu Z, Yan M, Fu A, Yin P. 2016. Geographic distributions in hypertension diagnosis, measurement, prevalence, awareness, treatment and control rates among middle-aged and older adults in China. Sci Rep. 6:1–11. doi:10.1038/srep37020.

Yong C, Yun L, Li LM, He PP, Yu CQ. 2010. A longitudinal analysis of the relationship between diet, physical activity and blood pressure level in 9 Chinese provinces. Chinese J Epidemiol. 5:500–505.

Zhou M, Wang H, Zeng X, Yin P, Zhu J, Chen W, Li X, Wang L, Wang L, Liu Y, et al. 2019. Mortality, morbidity, and risk factors in China and its provinces, 1990–2017: a systematic analysis for the global burden of disease study 2017. The Lancet. 394:1145–1158. doi:10.1016/S0140-6736(19)30427-1.