Environmental Science and Pollution Research (2022) 29:23905–23918
https://doi.org/10.1007/s11356-021-17406-5

RESEARCH ARTICLE

Does air pollution contribute to urban–rural disparity in male lung cancer diseases in China?

Huagui Guo[1] · Weifeng Li[2,3] · Jiansheng Wu[4,5] · Hung Chak Ho[2]

Received: 2 August 2021 / Accepted: 3 November 2021 / Published online: 24 November 2021

Abstract

It remains unknown whether exposure to ambient air pollution can be a mediator linking socioeconomic indicator to health outcome. The present study aims to examine the mediation effect of $PM_{2.5}$ air pollution on the association between urban–rural division and the incidence (mortality) rate of male lung cancer. We performed a nationwide analysis in 353 counties (districts) of China between 2006 and 2015. A structural equation model was developed to determine the mediation effect of exposure to $PM_{2.5}$. We also tested whether the findings of the mediation effect of exposure to $PM_{2.5}$ are sensitive to the controls of smoking factors and additional air pollutant, and $PM_{2.5}$ exposures with different lag structures. According to the results, we found that exposure to $PM_{2.5}$ significantly mediated the association between urban–rural division and the incidence rate of male lung cancer. Specifically, there were significant associations between urban–rural division, exposure to $PM_{2.5}$, and the incidence rate of male lung cancer, with $PM_{2.5}$ exposure accounting for 29.80% of total urban–rural difference in incidence rates of male lung cancer. A similar pattern of results was observed for the mortality rate of male lung cancer. That is, there was a significant mediation effect by $PM_{2.5}$ on the association of the mortality rate with urban–rural division. The findings of exposure to $PM_{2.5}$ as a mediator were robust in the three sensitivity analyses. In conclusion, urban–rural difference in exposures to $PM_{2.5}$ may be a potential factor that contributes to urban–rural disparity in male lung cancer diseases in China. The findings inform that air pollution management and control may be effective measures to alleviate the great difference in male lung cancer diseases between urban and rural areas in China.

Keywords Urban–rural division · Air pollution · Mediation effect · Lung cancer · China

Introduction

Socioeconomic disparities in health outcomes have been well documented. However, socioeconomic statuses do not affect human health directly. Hence, it is essential to understand mediators (pathways) linking socioeconomic factors to health outcomes. Exposure to air pollution is a potential mediator that can explain socioeconomic disparities in health outcomes. However, whether air pollution exposure mediates the relationship between socioeconomic status and human health has not been well and fully understood in China.

Previous studies have investigated associations between socioeconomic status, air pollution and health outcome.

Responsible Editor: Lotfi Aleya

✉ Hung Chak Ho
hcho21@hku.hk

Huagui Guo
huaguiguo@gmail.com

Weifeng Li
wfli@hku.hk

Jiansheng Wu
wujs@pkusz.edu.cn

1 School of Architecture and Urban-Rural Planning, Fuzhou University, Fuzhou 350108, China

2 Department of Urban Planning and Design, The University of Hong Kong, Hong Kong, China

3 Shenzhen Institute of Research and Innovation, The University of Hong Kong, Shenzhen 518057, China

4 Key Laboratory for Urban Habitat Environmental Science and Technology, Shenzhen Graduate School, Peking University, Shenzhen 518055, China

5 Key Laboratory for Earth Surface Processes, Ministry of Education, College of Urban and Environmental Sciences, Peking University, Beijing 100871, China

With respect to socioeconomic disparities in air pollution exposures, how disparity in exposures to air pollution occurs has been understood on the basis of several theories, such as market dynamics, racial discrimination and urbanization (Brulle and Pellow 2006; Mohai et al. 2009; Cesaroni et al. 2010; Padilla et al. 2014). Empirically, some studies have reported the significant association between socioeconomic status and air pollution exposure (Hajat et al. 2013; Bravo et al. 2016; Xu et al. 2019). In particular, collecting data from the project EURO-HEALTHY, a European study suggested that unemployment rate is positively associated with NO_2 concentration in nine metropolitan areas of Europe (Samoli et al. 2019). Combining data of mobile phone location, estimated $PM_{2.5}$ concentrations and housing price, a study reported that there is a significant association between economic status and individual total $PM_{2.5}$ exposure in Shenzhen, China (Guo et al. 2020a, b).

Regarding the association between air pollution and health outcome, biologically, air pollution can cause detrimental effects on human health through the increase in genetic damage such as cytogenetic abnormalities (International Agency for Research on Cancer (Volume 109), 2016a), oxidative stress, and inflammation (Lodovici and Bigagli 2011). A large number of studies have also indicated the adverse effects of air pollution on human's physical health (Pope et al. 2002; Pope and Dockery 2006; Chen et al. 2017) as well as psychological health (Power et al. 2015; Salinas-Rodríguez et al. 2018). It has also been reported that health consequences vary with race (Redmond et al. 2011), behavior factors (International Agency for Research on Cancer (Volume 83), 2016c; Rasmussen-Torvik et al. 2016) and socioeconomic indicators including urban–rural division, income and educational attainment (Cohen and Pope 3rd 1995; Fang et al. 2010; Evandrou et al. 2014).

Building on the work above, few studies have attempted to examine the mediation effect of air pollution exposure. It is hypothesized that socioeconomic status is associated with air pollution exposure, which in turn affects the physical and psychological health of human beings. Empirically, most of the studies generally suggest the mediation role of air pollution exposure on socioeconomic disparities in health outcomes, although the number of studies is small. Collecting health data of 6,463 adults from the Multi-ethnic Study of Atherosclerosis (MESA), Song et al. (2020) reported the significant mediation effect of exposure to ambient $PM_{2.5}$ on the association between race/ethnicity and systolic blood pressure across six cities of USA. Using county-level birth certificate data acquired from the National Centre for Health Statistics of the USA, Woodruff et al. (2003) indicated that the difference in exposures to air pollution among racial groups can partly account for racial disparity in preterm deliveries. Benmarhnia et al. (2017) suggested that $PM_{2.5}$ does explain a proportion of racial disparity in preterm births in California of the USA, although the effect of this air pollutant is quite small.

Despite these efforts, more studies are required due to the following reasons. Firstly, such studies are quite limited, hence it is not sufficient to conclude the mediation effect of air pollution exposure. Secondly, most of studies investigating the mediation effect of air pollution exposure focus on racial disparity (Woodruff et al. 2003; Hackbarth et al. 2011; Song et al. 2020), although racial issue is not popular or does not exist in many countries such as China. This highlights the more and further examinations in other contexts. Thirdly, few studies have investigated the determinants of urban–rural disparity in lung cancer diseases in China. Lung cancer has been the number one cause of cancer incidences (and mortalities) in China with age-adjusted incidence rate of lung cancer at 36.54 per 100, 000 people in 2014 (He and Chen 2018). Also, the large difference in lung cancer diseases between urban and rural areas (counties Vs. districts) has been well documented in China and other countries (Cohen and Pope 3rd 1995; Dikshit et al. 2012; He and Chen 2018; International Agency for Research on Cancer (Volumn 168), 2019) with age-adjusted incidence rate of male lung cancer at 54.15 per 100,000 people in urban areas and at 49.06 per 100,000 people in rural China in the present study. Meanwhile, a number of studies have suggested the adverse effects of air pollution (especially $PM_{2.5}$ which is highly severe and prominent in Chinese cities) on lung cancer diseases (Pope et al. 2002; International Agency for Research on Cancer (Volume 109), 2016a; Guo et al. 2020a). However, it remains unknown whether air pollution exposure can explain urban–rural disparity in lung cancer diseases in China.

To fill the gaps above, this work aims to investigate the mediation effect of exposure to $PM_{2.5}$ on the association between urban–rural division and the incidence (mortality) rate of male lung cancer in 353 Chinese cancer registries (counties/districts). The mediation effect was examined using a structural equation model which controlled for time, location and socioeconomic indicators. Moreover, we tested whether the findings of the mediation effect of air pollution exposure are sensitive to the controls of health and behavior factors (e.g., smoking behavior) and additional air pollutant, and $PM_{2.5}$ exposures with different lag structures (single- and moving-average lags).

Materials and methods

Research area

The present study is to investigate the mediation effect of exposure to $PM_{2.5}$ on urban–rural disparity in lung cancer diseases in 353 cancer registries of China. The number of urban (districts) and rural (counties) registries were 88 and 265, respectively. The 353 cancer registries were selected mainly due to the available data on health outcomes and socioeconomic indicators. Home to about 190.21 million in 2014, these registries are located in 31 of 34 Chinese provinces, autonomous regions and municipalities. Figure 1 presents the spatial distributions of 353 Chinese cancer registries.

Data collection

Annual mean $PM_{2.5}$ concentrations

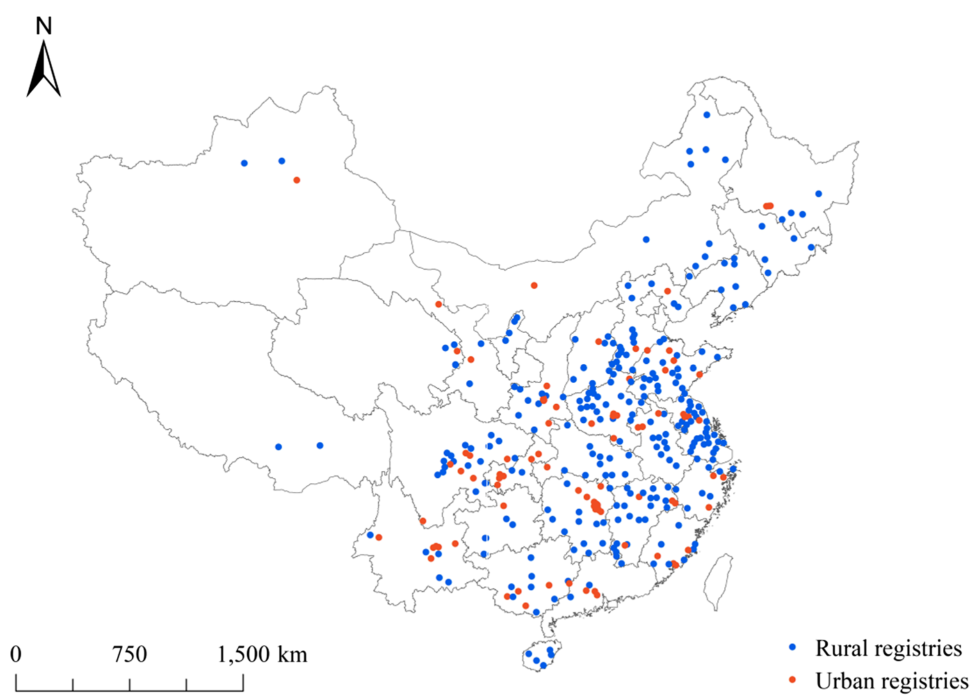
The targeted variable of air pollution is annual mean $PM_{2.5}$ concentrations, which are aggregated in each registry. Severe $PM_{2.5}$ air pollution in Chinese cities has received great attention from the public, scholars, and governments. Numerous studies have also provided the mechanisms and empirical evidences of $PM_{2.5}$ effects on human health including lung cancer diseases as health outcome in this work (International Agency for Research on Cancer (Volume 109), 2016a; Yin et al. 2017; Guo et al. 2020a). Accordingly, $PM_{2.5}$ is selected as the variable of air pollution to examine its mediation effect in the present study.

Data on annual ground $PM_{2.5}$ concentrations with spatial resolution at 1 km^2 from 2000 to 2015, were collected from the dataset of China Regional Estimates (V4.CH.02) publicly released by the Atmospheric Composition Analysis Group of Dalhousie University (http://fizz.phys.dal.ca/~atmos/martin/?page_id=140). Notably, data between 2006 and 2015 are used to examine the mediation effect of exposure to $PM_{2.5}$, while those from 2000 to 2015 are utilised to test the robustness of $PM_{2.5}$ mediation effect in the sensitivity analysis. More details of $PM_{2.5}$ data produced can refer to Van Donkelaar et al. (2016). Briefly, three satellite instruments, namely the NASA Moderate Resolution Imaging Spectroradiomete, Multi-angle Imaging Spectroradiometer and Sea-Viewing Wide Field-of-View Sensor, were used to retrieve AOD. Then, a GEOS-Chem chemical transport model was used to associate the retrieved AOD to near-surface $PM_{2.5}$ concentrations, which subsequently produced the time-series dataset of ground $PM_{2.5}$ concentrations at 1 km^2 spatial resolution from 2000 to 2017. Notably, there was residual bias in the initial satellite-derived values of $PM_{2.5}$. As a response, a geographically weighted regression model, in combination with ground-based measurements, was used to adjust for such residual bias. According to the results of validation, the estimated $PM_{2.5}$ was highly in line with the value derived from the monitoring measurement with R^2 equal to 0.81 (Van Donkelaar et al. 2015). To date, this dataset has been widely used in $PM_{2.5}$-associated studies (Han et al. 2018; Li et al. 2018; Wang et al. 2019; Liu et al. 2020). Figure 2(A–B) shows the spatial distributions of $PM_{2.5}$ concentrations in 2014 and 2015, respectively.

Annual age-standardized incidence (mortality) rate of male lung cancer

Data on annual age-standardized incidence (mortality) rate of male lung cancer (i.e., male trachea, bronchus and lung cancer) for each of 353 counties (districts) from 2006 to 2015 were acquired from the 2009–2018 China Cancer Registry

Fig. 1 Research area



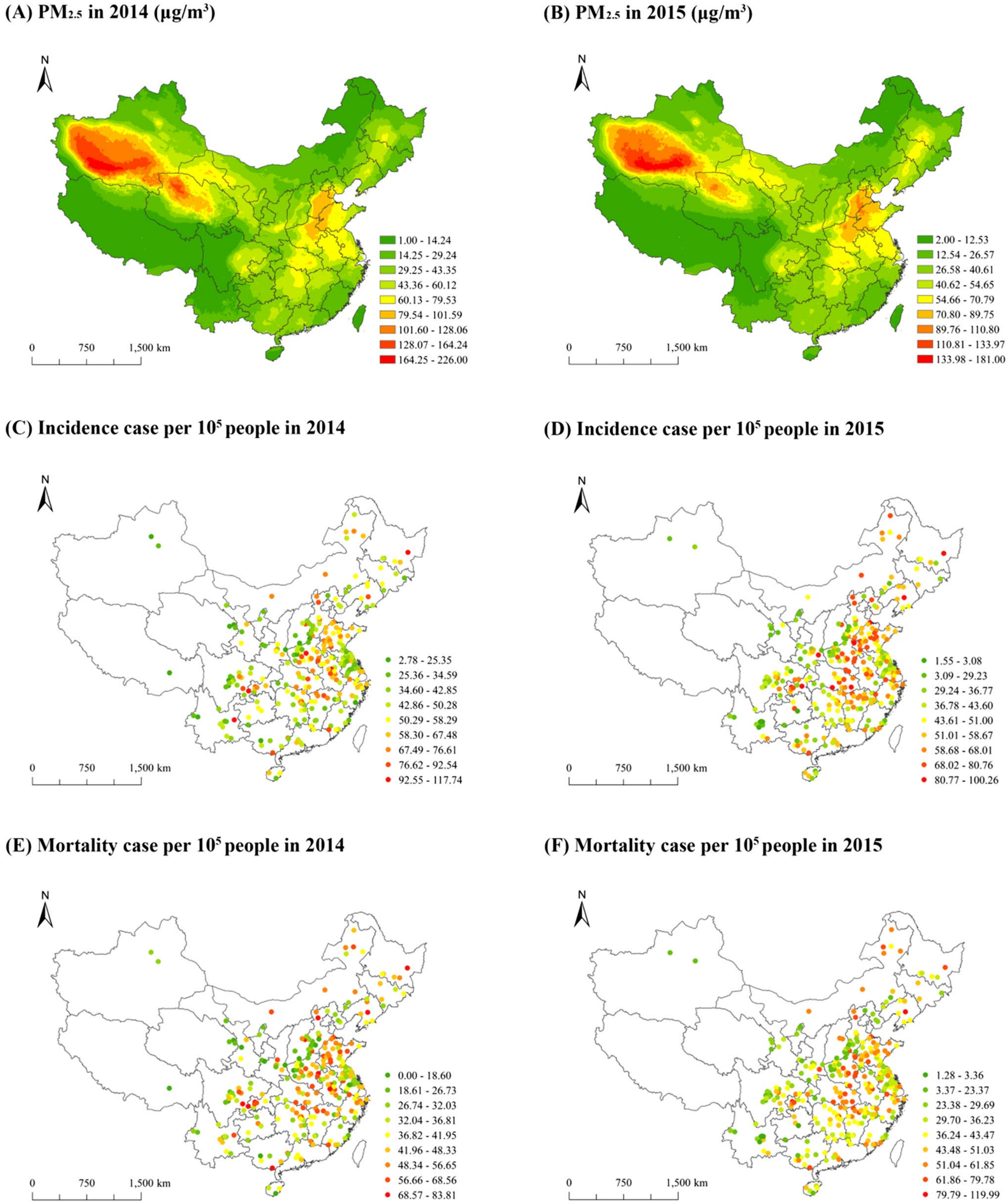


Fig. 2 Spatial distributions of $PM_{2.5}$ and the incidence (mortality) rate of male lung cancer in 2014 and 2015

Annual Report. The age-standardized incidence (mortality) rate is defined as the number of incidents (deaths) of male lung cancer per 100,000 people per year in a given county (district), and then the number was age-standardized according to the Segi's world population. The reports used in the present study were released by the Chinese Cancer Registry, National Cancer Centre of China. In these reports, the causes (e.g., lung cancer) of cancers have been specified according to the International Classification of Diseases version 10. The aim of the establishment of cancer registry in China is mainly to provide the timely and important information of cancer development across China (e.g., the number and rate of cancer incidence), which thus is highly representative at national scale. In particular, the 2017 China Cancer Registry Annual Report publicly released data of cause-specific cancer incidence (mortality) for 339 cancer registries (i.e., city, counties, districts, suburban areas of city) in 2014 (He and Chen 2018). These registries covering a population of more than 288 million residents in 2014, are dispersed over 31 of 34 Chinese province-level administrative units (He and Chen 2018). Figure 2(C–F) presents the spatial distributions of the incidence (mortality) rate of male lung cancer in 2014 and 2015.

Socioeconomic indicators, time and location covariates

We extracted socioeconomic data from multiple sources, namely the China Statistical Yearbook (County level), Tabulation of the 2010 Population Census of the People's Republic of China and China Cancer Registry Annual Report. Socioeconomic covariates controlled in the present study include urban–rural division (dummy variable), finance per capita (10^8 RMB), proportion of manufacturing workers (%), proportion of construction workers (%) and population size (10^4 people). These variables were selected to adjust for the differential health outcomes in relation to economic status, occupation and socioeconomic status based on the availability of data and the findings of previous studies (Cohen and Pope 3rd 1995; Elo 2009; Zhou et al. 2015).

Notably, the information of urban and rural division was derived from the China Cancer Registry Annual Report which uses districts and counties to represent urban and rural situations in China, respectively (He and Chen 2018). In China, it is of great significance to monitor and understand cancer burden in the respective urban and rural settings. Such operationalization is used to inform the design of policies and strategies for cancer preventions and controls which are tailored for the respective urban and rural settings at national scale. In the present study, the mean urbanization rates for districts and counties were 71.27% and 38.26%, respectively, which can well represent the urban and rural settings in China. The operationalization of the use of districts and counties to examine urban–rural disparities has been extensively adopted in many Chinese studies (Liu et al. 2015; Cui et al. 2016; Hu et al. 2019a, b).

Health and behavior factors

The variables of health and behavior include smoking prevalence, smoking strength (i.e. number of cigarettes smoked per day), alcohol consumption, and diabetes, which have shown their significant associations with lung cancer diseases in previous studies (International Agency for Research on Cancer (Volumes 44 and 83), 2016c). Data of the four variables were extracted from the 2015 China Health and Retirement Longitudinal Study (CHARLS) wave3 (specifically, the module of health status and functioning), publicly released by the National School of Development of Peking University. As a high-quality nationally representative survey, CHARLS wave3 is to assess the health conditions of Chinese residents with ages 45 or older. This survey recruited 12,400 households and 23,000 individuals that are located in 28 of 34 Chinese province-level administrative regions.

Statistical analysis

Structural equation model (SEM) was used to investigate the mediation effect of air pollution exposure on the association between urban–rural division and the incidence (mortality) rate of male lung cancer. SEM is a simultaneous equations system, which simultaneously combines multiple analyses such as regression analysis and path analysis. This model can not only facilitate the investigation of associations within and among groups of endogenous and exogenous factors, but also help to examine these factors' direct, indirect and total effects on each other. More details of SEM can refer to Bollen and Long (1993) and Golob (2003). To date, SEM has been widely used in many fields such as built environment and travel behavior (Bagley and Mokhtarian 2002; Cao et al. 2007). Also, this model has been increasingly used in environmental health studies (Fyhri and Klæboe 2009; Liu et al. 2019; Song et al. 2020).

In the present study, SEM was used to simultaneously examine the association between urban–rural division and the incidence (mortality) rate of male lung cancer (total association), the effect of urban–rural division on the incidence (mortality) rate of male lung cancer while controlling for ambient $PM_{2.5}$ exposure and other covariates (direct association), and the extent that the difference in $PM_{2.5}$ exposures between urban and rural areas can explain urban–rural disparity in incidence (mortality) rates of male lung cancer (indirect association). That is, the effect of urban–rural division on the incidence (mortality) rate of male lung cancer can be decomposed into an indirect effect (through air pollution exposure) and a direct effect (through other pathways). It is hypothesized that the difference in urban–rural statuses can not only cause differential $PM_{2.5}$ exposures, but also lead to disparity in incidence (mortality) rates of male lung cancer. Since ambient $PM_{2.5}$ can adversely affect lung cancer outcomes, the difference in PM2.5 exposures between urban and rural areas may account for urban–rural difference in incidence (mortality) rates of male lung cancer. More specifically, two equations were modelled. The first one modelled exposure to ambient $PM_{2.5}$ as a function of urban–rural division, adjusting for time, location and other socioeconomic factors including finance per capita, proportion of manufacturing workers, proportion of construction workers and population size. The second equation modelled the incidence (mortality) rate of male lung cancer as a function of urban–rural division, controlling for exposure to ambient $PM_{2.5}$ and all covariates included in the first equation. Notably, the selection of socioeconomic indicators in the two equations was based on the findings of previous environmental health studies (Hajat et al. 2013; Evandrou et al. 2014; Huang et al. 2019).

Three sensitivity analyses were performed. Firstly, we tested the sensitiveness of the mediation effect of exposure to $PM_{2.5}$ to the control of health and behavior factors. Based on data availability and the findings of previous lung cancer studies (International Agency for Research on Cancer (Volumes 44 and 83), 2016), four factors including smoking prevalence, smoking strength (i.e. number of cigarettes smoked per day), alcohol consumption and diabetes were selected for such adjustments. Since the CHARLS survey does not cover all counties/districts of the present study, we kept samples located in the cities of the CHARLS survey, which left around half of original samples for the sensitivity analysis. Also, data of health and behavior we can access are available at the level of prefectural city, so we attributed districts/counties within the same city with the same health and behavior characteristics. Secondly, we examined whether the mediation effect of exposure to ambient $PM_{2.5}$ is robust to the adjustment of additional air pollutant (i.e., SO_2), because some studies suggested that the lack of additional air pollutant control may obscure the mediation effect of the targeted air pollution (Song et al. 2020). Thirdly, we tested whether the mediation effect of exposure to ambient $PM_{2.5}$ is sensitive to $PM_{2.5}$ exposures with different lag structures (i.e., single- and moving-average lags), because there is the potential latency of the development of lung cancer consequences as indicated in many previous studies (Garshick et al. 2012; Guo et al. 2020a; Chung et al. 2021).

Results

Descriptive analysis

The results of the descriptive statistics of air pollutants, health outcomes, and some socioeconomic factors between urban and rural areas are shown in Table 1. The mean $PM_{2.5}$ concentrations was 51.71 μg/m^3 in urban areas, which was higher than that of rural areas at 49.97 μg/m^3 (Table 1); moreover, $PM_{2.5}$ concentrations also varied greatly among urban and rural groups with the standard deviation at 18.62 and 18.82, respectively (Table 1). With regard to the mean incidence rate of male lung cancer, it was 54.15 per 100,000 people and 49.06 per 100,000 people in urban and rural areas, respectively, which demonstrated the potential of urban–rural disparity in incidence rates (Table 1); the great variations in incidence rates of urban and rural groups were also observed. A similar pattern of results was found for the mortality rate of male lung cancer. In particular, as shown in Table 1, the mean mortality rate was higher in urban than in rural areas with observed values at 43.91 per 100,000 people and 39.52 per 100,000 people, respectively. Also, there were great difference in additional air pollutants and some socioeconomic indicators between urban and rural groups (Table 1).

Mediation effects of air pollution

Tables 2 and 4 present the results of $PM_{2.5}$ as a mediator linking urban–rural division and the incidence rate. In general, $PM_{2.5}$ significantly mediated the association between

Table 1 Descriptive statistics of air pollutants, health outcomes and some socioeconomic factors between urban and rural areas

Variables	Areas	Min	Mean	SD	Max
$PM_{2.5}$ (μg/m^3)	Urban	11.21	51.71	18.62	90.91
	Rural	2.40	49.97	18.82	100.73
SO2 (μg/m3)	Urban	1.38	26.28	12.80	49.76
	Rural	0.09	29.29	14.52	65.73
Incidence rate (per 10^5 people)	Urban	1.55	54.15	17.52	125.51
	Rural	2.78	49.06	16.63	117.74
Mortality rate (per 10^5 people)	Urban	1.28	43.91	15.54	119.99
	Rural	0.00	39.52	13.65	94.32
Finance per capita (108 RMB)	Urban	0.28	29.63	61.95	802.73
	Rural	0.22	19.85	21.07	284.76
Construction (%)	Urban	0.09%	0.37%	0.24%	3.14%
	Rural	0.04%	0.33%	0.19%	1.02%
Manufacturing (%)	Urban	0.13%	0.93%	0.75%	3.96%
	Rural	0.02%	0.88%	0.82%	4.21%

Table.2 Association between urban–rural division and incidence rate: $PM_{2.5}$ as a mediator

Variables	Direct		Indirect		Total	
	β	95% CI	β	95% CI	β	95% CI
Urban–rural	3.39 ***	(1.49, 5.35)	1.44 ***	(0.91, 2.05)	4.83 ***	(2.85, 6.85)
Air pollution	0.31 ***	(0.25, 0.38)	-	-	0.31 ***	(0.25, 0.38)
Lat	-6.18 ***	(-7.81, -4.66)	5.08 ***	(4.10, 6.19)	-1.11 *	(-2.29, 0.00)
Lat^2	0.09 ***	(0.07, 0.11)	-0.07 ***	(-0.09, -0.06)	0.02 **	(0.00, 0.04)
Year 2007	2.37	(-5.55, 10.54)	0.42	(-1.42, 2.15)	2.79	(-4.99, 10.82)
Year 2008	3.87	(-3.69, 11.11)	-0.99	(-2.74, 0.45)	2.88	(-4.63, 10.24)
Year 2009	3.59	(-3.01, 10.02)	-1.03	(-2.74, 0.31)	2.56	(-4.01, 8.95)
Year 2010	5.54	(-0.41, 11.61)	-0.63	(-2.20, 0.62)	4.91	(-0.85, 10.99)
Year 2011	8.52 **	(2.69, 14.61)	-1.95 **	(-3.56, -0.76)	6.56 **	(0.72, 12.45)
Year 2012	11.87 ***	(6.05, 18.06)	-3.04 ***	(-4.76, -1.77)	8.84 ***	(3.01, 14.98)
Year 2013	9.50 ***	(3.70, 15.26)	-0.68	(-2.26, 0.55)	8.82 ***	(2.94, 14.42)
Year 2014	9.33 ***	(3.79, 15.25)	-1.05	(-2.58, 0.16)	8.28 ***	(2.86, 14.16)
Year 2015	8.04 ***	(2.56, 14.28)	-1.92 ***	(-3.51, -0.73)	6.12 **	(0.49, 12.10)
Finance	-0.00	(-0.03, 0.03)	-0.00	(-0.01, 0.01)	-0.00	(-0.03, 0.02)
Construction [a]	4.48 **	(0.52, 8.75)	-2.17 ***	(-3.39, -1.21)	2.31	(-1.63, 6.55)
Manufacturing [a]	-0.28	(-1.40, 0.83)	0.16	(-0.14, 0.45)	-0.13	(-1.25, 0.92)
Population	0.05 ***	(0.02, 0.07)	0.04 ***	(0.03, 0.05)	0.09 ***	(0.06, 0.11)

* for $P < 0.1$, ** for $P < 0.05$ and *** for $P < 0.01$. [a] for value = original value × 100

urban–rural division and the incidence rate. The incidence rate of male lung cancer significantly varied between urban and rural areas, which indicated the existence of urban–rural disparity in incidence rates of male lung cancer. The total and direct effects of urban–rural division were 4.83 (95% CI: 2.85, 6.85), and 3.39 (95% CI: 1.49, 5.35), respectively, which suggested that there was an indirect effect. Regarding the indirect effect of urban–rural division through the impact on exposure to $PM_{2.5}$, exposure significantly varied between urban and rural areas (β = 4.64, 95% CI: 3.08, 6.26) with residents living in urban areas exposed to high levels of air pollution concentrations (Table 4); also, the association between $PM_{2.5}$ exposure and the incidence rate of male lung cancer was significant (Table 2); more importantly, there was a significant difference in incidence rates by urban–rural division that was associated with $PM_{2.5}$ exposure (the indirect effect) (β = 1.44, 95% CI: 0.91, 2.05), namely air pollution exposure accounted for 29.80% of total urban–rural difference in incidence rates of male lung cancer in China (Table 2).

The results of the mediation effect by $PM_{2.5}$ on the association of mortality rate with urban–rural division are shown in Tables 3 and 4. Generally, there was a significant mediation effect by $PM_{2.5}$. As shown in Table 3, there was a significant difference in mortality rates of male lung cancer between urban and rural areas. This suggested the existence of disparity in mortality rates by urban–rural division. The direct and indirect effects of urban–rural division were 2.97 (95% CI: 1.37, 4.76) and 4.07 (95% CI: 2.38, 5.84), respectively. Regarding the indirect effect of urban–rural division (rural areas as the reference), such division was positively associated with exposure to $PM_{2.5}$ air pollution (β = 4.64, 95% CI: 3.08, 6.26), namely people residing in urban areas suffered from disproportionate exposures to air pollution (Table 4); there was a positive effect of $PM_{2.5}$ on the mortality rate of male lung cancer (as shown in Table 3); $PM_{2.5}$-associated difference in mortality rates between urban and rural areas was also significant (β = 1.09, 95% CI: 0.68, 1.56), namely the proportion of urban–rural difference in mortality rates of male lung cancer attributable to $PM_{2.5}$ exposures was 26.85%.

Sensitivity analysis

Adjustment of health and behavior factors

Figure 3 presents the results of the sensitivity analysis adjusting for health and behavior factors. In general, the findings of the mediation role of $PM_{2.5}$ was not sensitive to the control of such factors. Without the adjustment of health and behavior covariates (Fig. 3(A)), there was a significant difference in incidence rates of male lung cancer by urban–rural division due to differential exposures to $PM_{2.5}$ between urban–rural areas; $PM_{2.5}$ was positively associated with the incidence rate (Fig. 3(A)). After the control of health and behavior covariates (Fig. 3(B)), urban–rural difference in incidence rates of male lung cancer, which was related to differential $PM_{2.5}$ exposures (i.e., the indirect effect of urban–rural division through the impact on exposure to $PM_{2.5}$), was still significant;

Table.3 Association between urban–rural division and mortality rate: $PM_{2.5}$ as a mediator

Variables	Direct		Indirect		Total	
	β	95% CI	β	95% CI	β	95% CI
Urban–rural	2.97 ***	(1.37, 4.76)	1.09***	(0.68, 1.56)	4.07***	(2.38, 5.84)
Air pollution	0.24***	(0.19, 0.29)	-	-	0.24***	(0.19, 0.29)
Lat	-5.18***	(-6.51, -3.99)	3.85***	(3.04, 4.78)	-1.33***	(-2.30, -0.40)
Lat^2	0.08***	(0.06, 0.10)	-0.06***	(-0.07, -0.04)	0.02***	(0.01, 0.04)
Year 2007	3.92	(-3.11, 11.14)	0.32	(-1.07, 1.65)	4.24	(-2.65, 11.56)
Year 2008	3.45	(-3.18, 10.24)	-0.75	(-2.07, 0.34)	2.70	(-3.90, 9.44)
Year 2009	3.49	(-1.82, 8.84)	-0.78	(-2.14, 0.22)	2.71	(-2.70, 8.05)
Year 2010	2.86	(-2.13, 8.04)	-0.48	(-1.65, 0.48)	2.38	(-2.54, 7.64)
Year 2011	5.08	(-0.04, 10.14)	-1.48***	(-2.73, -0.56)	3.60	(-1.45, 8.69)
Year 2012	8.56***	(3.24, 13.66)	-2.31***	(-3.67, -1.31)	6.26**	(1.14, 11.46)
Year 2013	6.47**	(1.34, 11.42)	-0.52	(-1.73, 0.42)	5.96**	(0.93, 10.83)
Year 2014	6.78**	(1.82, 11.61)	-0.80	(-2.03, 0.09)	5.98**	(1.03, 10.90)
Year 2015	7.01**	(2.03, 12.01)	-1.46***	(-2.75, -0.54)	5.55**	(0.64, 10.56)
Finance	0.00	(-0.02, 0.02)	-0.00	(-0.01, 0.00)	0.00	(-0.02, 0.02)
Construction [a]	3.29	(-0.44, 7.53)	-1.64***	(-2.57, -0.89)	1.64	(-2.08, 5.91)
Manufacturing [a]	0.83	(-0.06, 1.61)	0.12	(-0.10, 0.34)	0.95*	(0.08, 1.70)
Population	0.05***	(0.03, 0.07)	0.03***	(0.02, 0.04)	0.08***	(0.06, 0.10)

[*] for $P<0.1$, ** for $P<0.05$ and *** for $P<0.01$. [a] for value = original value × 100

Table.4 Association between urban–rural division and $PM_{2.5}$

Variables	β	95% CI
Urban–rural	4.64***	(3.08, 6.26)
Lat	16.39***	(15.46, 17.44)
Lat^2	-0.23***	(-0.25, -0.22)
Year 2007	1.35	(-4.75, 6.84)
Year 2008	-3.20	(-8.57, 1.56)
Year 2009	-3.32	(-8.81, 1.12)
Year 2010	-2.05	(-6.82, 2.12)
Year 2011	-6.31**	(-10.95, -2.34)
Year 2012	-9.80***	(-14.59, -5.56)
Year 2013	-2.19	(-6.85, 1.95)
Year 2014	-3.39	(-8.04, 0.62)
Year 2015	-6.21***	(-10.71, -2.26)
Finance	-0.01	(-0.04, 0.02)
Construction [a]	-6.99***	(-10.27, -3.56)
Manufacturing [a]	0.51	(-0.45, 1.38)
Population	0.14***	(0.11, 0.15)

[*] for $P<0.1$, ** for $P<0.05$ and *** for $P<0.01$. [a] for value = original value × 100

there was a significant effect of $PM_{2.5}$ on the incidence rate (Fig. 3(B)); significant associations between health and behavior factors and the incidence rate of male lung cancer were also observed (Fig. 3(B)). A similar pattern of results was observed for the mortality rate of male lung cancer (Fig. 3(C) and Fig. 3(D)). In particular, $PM_{2.5}$-related difference in mortality rates of male lung cancer between urban and rural areas was still significant after the adjustment of health and behavior covariates (Fig. 3(D)).

$PM_{2.5}$ exposures with different lag structures

The results of the sensitivity analysis using $PM_{2.5}$ exposures with different lag structures are shown in Fig. 4. In general, the mediation effect of $PM_{2.5}$ was robust to the different operationalization of $PM_{2.5}$ exposures. As shown in Fig. 4(A), there were significant associations of $PM_{2.5}$ at lag 1 with urban–rural division and the incidence rate of male lung cancer; the indirect effect of urban–rural division on the incidence rate through the impact on $PM_{2.5}$ at lag 1 (i.e., the difference in incidence rates by urban–rural division, which is associated with different exposures to $PM_{2.5}$ at lag 1) was positive (Fig. 4(A)); a similar pattern of results was observed for $PM_{2.5}$ exposures at each of single- and moving-average lags (i.e., lag 1 to lag 6, lag 01 to lag 06) in Fig. 4(A). With respect to the mortality rate (Fig. 4(B)), we found a pattern of results similar to those of incidence rate (Fig. 4(B)). In particular, the indirect effect of urban–rural division through the impact on exposures to $PM_{2.5}$ at each of $PM_{2.5}$ lags was still significant (Fig. 4(B)).

Adjustment of additional air pollutant

Figure 5 presents the results of the sensitiveness of $PM_{2.5}$ mediation effect to the adjustment of additional air pollutant (i.e., SO_2). In general, the results of the mediation role of $PM_{2.5}$ were robust to the control of additional air pollution

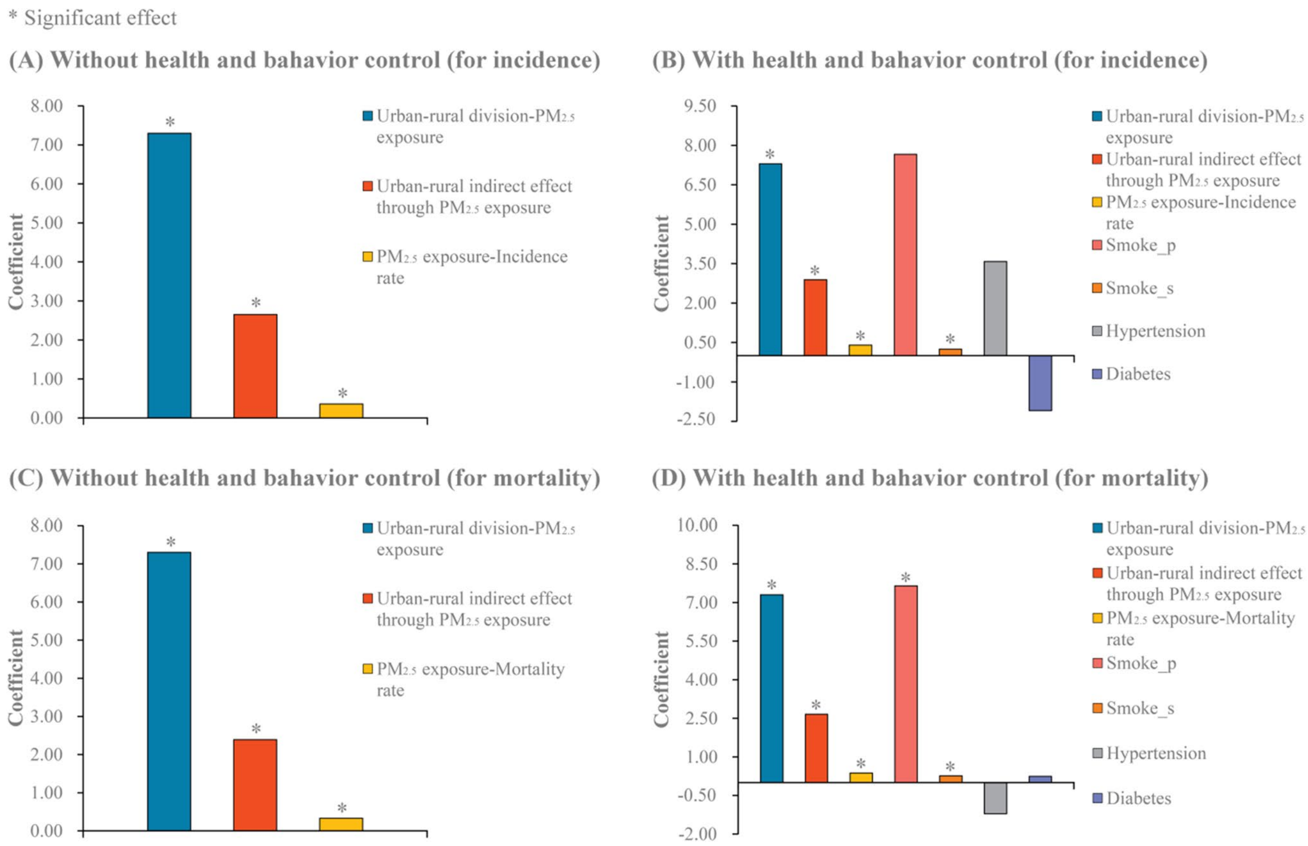


Fig. 3 Sensitivity analysis of $PM_{2.5}$ mediation effect to the adjustment of health and behavior factors

(namely SO_2). With the control of additional air pollutant (i.e., SO_2) in the structural equation model (Fig. 5(A)), $PM_{2.5}$ exposures varied between urban and rural areas, and the association between $PM_{2.5}$ and the incidence rate of male lung cancer was still positive; moreover, the mediation effect of $PM_{2.5}$ on the association of the incidence rate of male lung cancer with urban–rural division was still significant (Fig. 5(A)). A similar pattern of results could be observed for the mortality rate (Fig. 5(B)). Apart from the significant effect of urban–rural division on exposure to $PM_{2.5}$, for example, there was a significant difference in mortality rates by urban–rural division, which is related to differential $PM_{2.5}$ exposures (Fig. 5(B)).

Discussions

It is of great significance to determine factors potentially explaining socioeconomic disparities in human health. Despite the potential role of exposure to air pollution, it remains unknown whether exposure to air pollution mediates the relationship between socioeconomic status and health outcome. To remedy this issue, the present study examined whether there is a mediation effect of exposure to $PM_{2.5}$ (the prominent air pollutant in China) on the association of lung cancer disease with urban–rural division in China.

We found that exposure to $PM_{2.5}$ significantly varies between urban and rural areas. This finding is consistent with those of prior studies. For example, taking 35 prefecture-level cities of China as research area, Han et al. (2020) suggested that $PM_{2.5}$ air pollution is much more severe in urban than in rural areas, especially in summer. Similarly, Lin et al. (2012) reported considerable urban–rural variation in air pollution concentrations in North China. Urban–rural disparity observed in the present study is a dominant phenomenon in China and can also be found in the indicated effects of environmental elements such as air pollution and temperature (Guo et al. 2015; Hu et al. 2019a, b; Li et al. 2020) as well as smoking behaviors (Chen et al. 2015a, b). We found that there are significant associations of incidence (mortality) rate of male lung cancer with urban–rural division and exposure to $PM_{2.5}$. These two findings are in line with those of studies investigating urban–rural disparity in human health (Cohen and Pope 3rd 1995; Dikshit et al. 2012; He and Chen 2018; International Agency for Research on Cancer (Volumn 168) 2019) as well as the effects of air pollution (Pope and Dockery 2006; Chen et al. 2017;

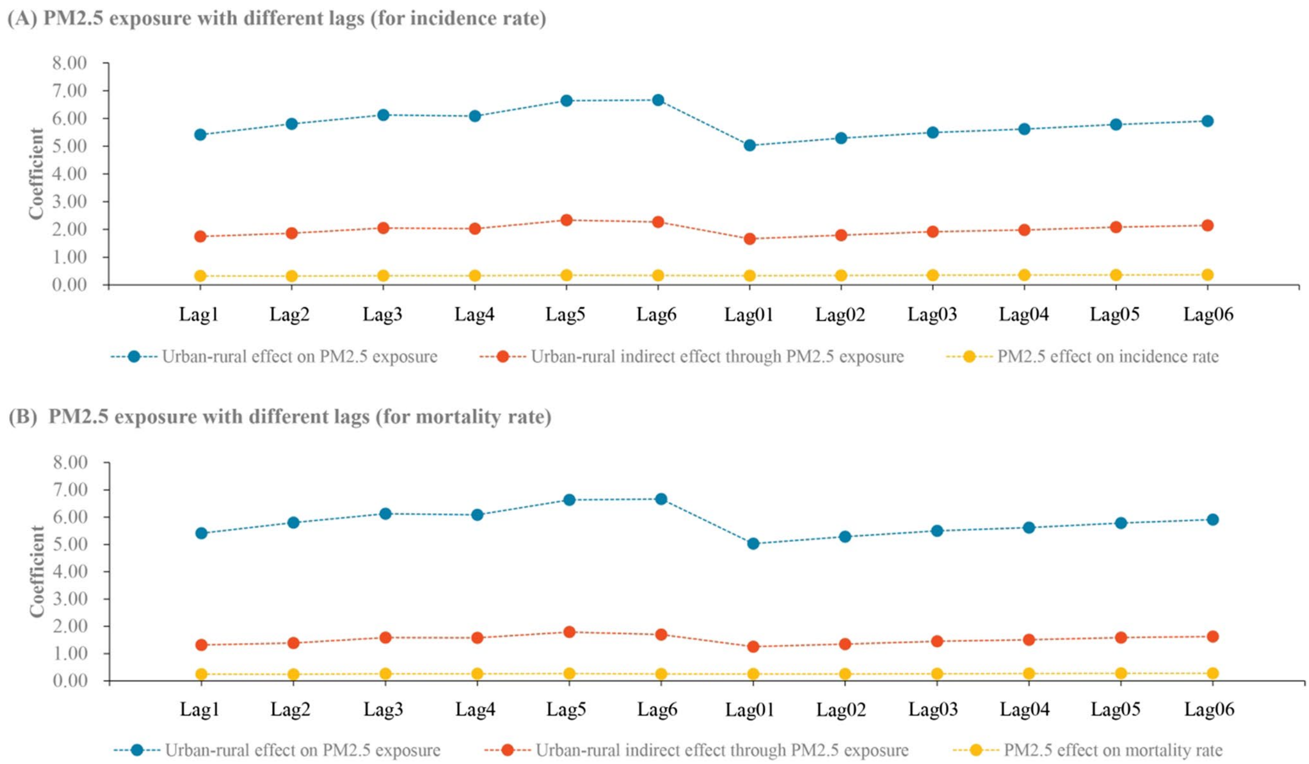


Fig. 4 Sensitivity analysis of mediation effect by $PM_{2.5}$ to $PM_{2.5}$ exposures with different lag structures

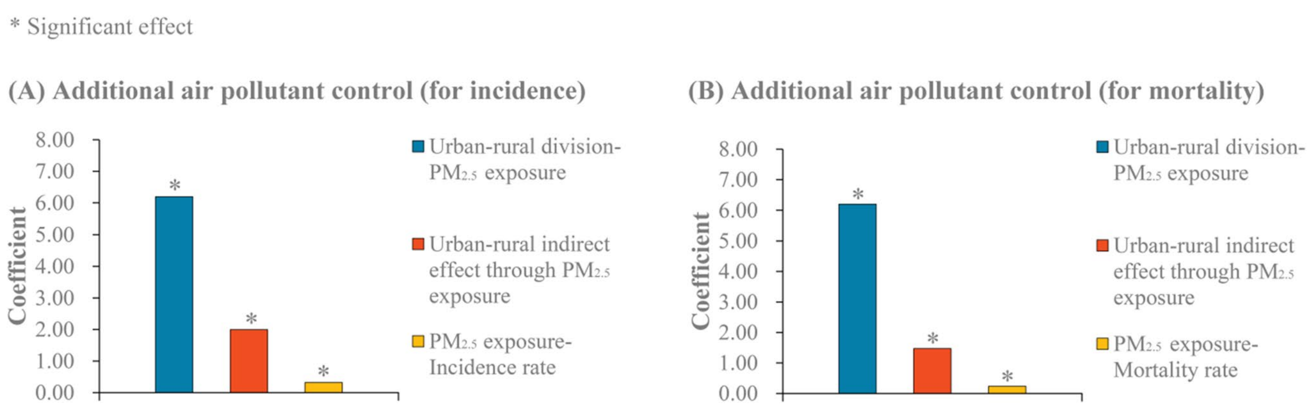


Fig. 5 Sensitivity analysis of mediation effect by $PM_{2.5}$ to the adjustment of additional air pollutant

International Agency for Research on Cancer (Volumn 168) 2016).

We found the mediation effect of exposure to $PM_{2.5}$ on the association between urban–rural division and the incidence (mortality) rate of male lung cancer in China. It is usually argued that the difference in air pollution exposures across socioeconomic groups can partly explain socioeconomic disparities in human health. The meditation role of exposure to air pollution observed in the present study is consistent with those of some prior studies. In particular, Schulz et al. (2020) reported that exposure to ambient $PM_{2.5}$ significantly mediates the association between race-based residential segregation and all-cause mortality at the level of census tract in the Detroit Metropolitan Area of United States. Using data collected from the nationally representative survey (i.e., Indagine Multiscopo sulle Famiglie), Franzini and Giannoni (2010) indicated that differential exposures to ambient air pollution are responsible for the difference in self-reported health statuses across socioeconomic groups at regional level of Italy. A similar pattern of results can be observed in relevant studies investigating the contribution of air pollution exposure to health disparities across racial groups (Woodruff et al. 2003; Benmarhnia et al. 2017; Song et al. 2020). Findings from the present study highlight that apart from smoking behaviors which are known as the most prominent risks of lung cancer (Chen et al. 2015a, b), the difference in exposures to air pollution between urban and rural areas may also contribute to the great urban–rural difference in lung cancer diseases in China.

There are several strengths and policy implications in the present study. Firstly, to our knowledge, this is one of the earliest attempts to investigate the potential role of $PM_{2.5}$ exposures to uncover urban–rural disparities in lung cancer diseases in China. Understanding socioeconomic (and racial) disparities in health outcomes requires a great emphasis on the discovery of contributors. Many studies focus on the determinants of such disparities from the perspectives of health and behavior factors (Basu et al. 2015; Rasmussen-Torvik et al. 2016), social factors (Kondo et al. 2008; Lorch and Enlow 2016) and access to or quality of health care (Bosworth et al. 2006). Instead, the present study provides insight into the determinants of urban–rural disparities in lung cancer diseases from the perspective of air pollution, which complements the knowledge on the mechanisms linking socioeconomic statuses to health outcomes in the literature. Secondly, we investigate the mediation effect of air pollution exposure in a setting (China) where urban–rural disparity is much more dominant, instead of racial issue popular in most prior studies (Woodruff et al. 2003; Hackbarth et al. 2011; Song et al. 2020). Thirdly, air pollution as a potential mediator identified in the present study not only provides a well understanding of the high burden of lung cancer diseases in urban than in rural areas in China, but also provides the potential to alleviate urban–rural disparities in lung cancer diseases in the same country through the control and management of air pollution (especially the prominent $PM_{2.5}$ air pollution in urban areas).

Several limitations and future research should be discussed. Firstly, ecological design of the present study which is similar to those of most prior ecological studies (Woodruff et al. 2003; Hackbarth et al. 2011; Schulz et al. 2020), suffers from inevitable problems such as estimate errors in $PM_{2.5}$ exposures as well as ecological fallacy. Like many studies (Hackbarth et al. 2011; Guo et al. 2015), the mean concentration of $PM_{2.5}$ aggregated at the geographic unit is used as the surrogate of exposure to $PM_{2.5}$ in the present study. Such operationalization of exposure to $PM_{2.5}$ does not consider variations in individual mobility and air pollution concentrations (i.e., the two key determinants of the estimate of air pollution exposure), which therefore may produce misclassification errors in exposure estimates (Yoo et al. 2015; Shafran-Nathan et al. 2018; Guo et al. 2020a, b) as well as ecological fallacy (Schwartz 1994). However, ecological studies (e.g. the present study) also have their strengths in broad area coverage as well as large sample (population) size. Cross-sectional ecological studies combined with studies using longitudinal individual-level data, would contribute to a more robust and scientific determination of air pollution mediation effect.

Secondly, the operationalization which uses smoking data at city level to test whether the mediation role of exposure to $PM_{2.5}$ is sensitive to the control of smoking factors, may ignore the variation in smoking situations across counties/districts belonging to the same city. If data on smoking covariates at county (district) level are available in the future, such limitation should be well addressed to warrant the findings of the mediation effect by air pollution exposure. Thirdly, like many previous studies examining the concurrent or longer time effect of air pollution (Garshick et al. 2012; Guo et al. 2015; Chung et al. 2021), the 6-year lag adopted to test the robustness of $PM_{2.5}$ mediation effect to $PM_{2.5}$ exposures with different lag structures (i.e., single- and moving-average lags) is likely to be insufficient to take the long latency of lung cancer development into account. This limitation should be fully considered, if air pollution data prior to 2000 and earlier are available in future work. Fourthly, pathways linking socioeconomic factors to human health have not been well understood from the perspectives of environmental elements such as temperature, soundscape and access and accessibility to public facilities (Hong et al. 2021). Future studies, especially epidemiological research, can target these issues to facilitate the understanding of socioeconomic disparities in human health.

Conclusions

Exposure to $PM_{2.5}$ meditates the association between urban–rural division and the incidence (mortality) rate of male lung cancer in China. That is, the difference in $PM_{2.5}$ air pollutions between urban and rural areas may be partly responsible for urban–rural disparity in male lung cancer diseases in China. Intervention strategies relevant to air pollution management and control should be well developed to reduce such great disparity.

Author contribution Dr. Huagui Guo conducted research design, data analysis and manuscript writing and revision. Dr. Weifeng Li and Prof. Jiansheng Wu performed data collection and manuscript revision. Dr. Hung Chak Ho contributed to research design and manuscript revision. All authors read and approved the final version of the manuscript.

Funding This work was supported by the Start-up Foundation of Fuzhou University (511034), Shenzhen Fundamental Research Program (GXWD20201231165807007-20200816003026001), 2021 Guangdong Natural Science Fund - General Programme

(2021A1515012571) and Guangdong - Hong Kong - Macau Joint Laboratory Program of the 2020 Guangdong New Innovative Strategic Research Fund, Guangdong Science and Technology Department (2020B1212030009).

Data availability The datasets analyzed during the current study available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

Bagley MN, Mokhtarian PL (2002) The impact of residential neighborhood type on travel behavior: A structural equations modeling approach. Ann Reg Sci 36(2):279–297

Basu S, Hong A, Siddiqi A (2015) Using decomposition analysis to identify modifiable racial disparities in the distribution of blood pressure in the United States. Am J Epidemiol 182(4):345–353

Benmarhnia T, Huang J, Basu R, Wu J, Bruckner TA (2017) Decomposition analysis of black–white disparities in birth outcomes: the relative contribution of air pollution and social factors in California. Environ Health Perspect 125(10):107003

Bollen KA, Long JS (1993) Testing structural equation models. Sage

Bosworth HB, Dudley T, Olsen MK, Voils CI, Powers B, Goldstein MK, Oddone EZ (2006) Racial differences in blood pressure control: potential explanatory factors. Am J Med 119(1):70-e9

Bravo MA, Anthopolos R, Bell ML, Miranda ML (2016) Racial isolation and exposure to airborne particulate matter and ozone in understudied US populations: environmental justice applications of downscaled numerical model output. Environ Int 92:247–255

Brulle RJ, Pellow DN (2006) Environmental justice: human health and environmental inequalities. Annu Rev Public Health 27:103–124

Cao X, Mokhtarian PL, Handy SL (2007) Do changes in neighborhood characteristics lead to changes in travel behavior? A structural equations modeling approach. Transportation 34(5):535–556

Cesaroni G, Badaloni C, Romano V, Donato E, Perucci CA, Forastiere F (2010) Socioeconomic position and health status of people who live near busy roads: the Rome Longitudinal Study (RoLS). Environ Health 9(1):41

Chen ZM, Peto R, Iona A, Guo Y, Chen YP, Bian Z, Yang L, Zhang W, Lu F, Chen J, Collins R, Li L, Li M (2015) Emerging tobacco-related cancer risks in China: A nationwide, prospective study of 0.5 million adults. Cancer 121(S17):3097–3106

Chen Z, Peto R, Zhou M, Iona A, Smith M, Yang L, Guo Y, Chen Y, Bian Z, Lancaster G, Sherliker B, Pang S, Wang H, Su H, Wu M, Wu X, Chen J, Collins R, Li M (2015b) Contrasting male and female trends in tobacco-attributed mortality in China: evidence from successive nationwide prospective cohort studies. The Lancet 386(10002):1447–1456

Chen R, Yin P, Meng X, Liu C, Wang L, Xu X, Ross J, Tse L, Zhao Z, Kan H, Zhou M (2017) Fine particulate air pollution and daily mortality. A nationwide analysis in 272 Chinese cities. Am J Respir Crit Care Med 196(1):73–81

Chung CY, Yang J, He J, Yang X, Hubbard R, Ji D (2021) An investigation into the impact of variations of ambient air pollution and meteorological factors on lung cancer mortality in Yangtze River Delta. Sci Total Environ 779:146427

Cohen AJ, Pope CA 3rd (1995) Lung cancer and air pollution. Environ Health Perspect 103(suppl 8):219–224

Cui H, He C, Kang L, Li Q, Miao L, Shen L, Zhu J, Li X, Wang Y (2016) Under-5-Years Child Mortality Due to Congenital Anomalies: A Retrospective Study in Urban and Rural China in 1996–2013. Am J Prev Med 50(5):663–671

Dikshit R, Gupta PC, Ramasundarahettige C, Gajalakshmi V, Aleksandrowicz L, Badwe R, Kumar R, Roy S, Suraweera W, Bray F, Mallath M, Singh P, Sinha D, Shet A, Gelband H, Jha P (2012) Cancer mortality in India: a nationally representative survey. The Lancet 379(9828):1807–1816

Elo IT (2009) Social class differentials in health and mortality: Patterns and explanations in comparative perspective. Ann Rev Sociol 35:553–572

Evandrou M, Falkingham J, Feng Z, Vlachantoni A (2014) Individual and province inequalities in health among older people in China: Evidence and policy implications. Health Place 30:134–144

Fang P, Dong S, Xiao J, Liu C, Feng X, Wang Y (2010) Regional inequality in health and its determinants: evidence from China. Health Policy 94(1):14–25

Franzini L, Giannoni M (2010) Determinants of health disparities between Italian regions. BMC Public Health 10(1):296

Fyhri A, Klæboe R (2009) Road traffic noise, sensitivity, annoyance and self-reported health—A structural equation model exercise. Environ Int 35(1):91–97

Galea S, Blaney S, Nandi A, Silverman R, Vlahov D, Foltin G, Kusick M, Richmond N (2007) Explaining racial disparities in incidence of and survival from out-of-hospital cardiac arrest. Am J Epidemiol 166(5):534–543

Garshick E, Laden F, Hart JE, Davis ME, Eisen EA, Smith TJ (2012) Lung cancer and elemental carbon exposure in trucking industry workers. Environ Health Perspect 120(9):1301–1306

Golob TF (2003) Structural equation modeling for travel behavior research. Transp Res B Methodol 37(1):1–25

Guo Y, Zeng H, Zheng R, Li S, Barnett AG, Zhang S, Zou X, Huxley R, Chen W, Williams G (2015) Lung cancer incidence and ambient air pollution in China: a spatial age–period cohort study 1990–2009. The Lancet 386:S5

Guo H, Li W, Wu J (2020) Ambient PM2. 5 and annual lung cancer incidence: a nationwide study in 295 Chinese counties. Int J Environ Res Public Health 17(5):1481

Guo H, Li W, Yao F, Wu J, Zhou X, Yue Y, Yeh AG (2020) Who are more exposed to PM2. 5 pollution: A mobile phone data approach. Environment International 143:105821

Hackbarth AD, Romley JA, Goldman DP (2011) Racial and ethnic disparities in hospital care resulting from air pollution in excess of federal standards. Soc Sci Med 73(8):1163–1168

Hajat A, Diez-Roux AV, Adar SD, Auchincloss AH, Lovasi GS, O'Neill MS, Sheppard L, Kaufman JD (2013) Air pollution and individual and neighborhood socioeconomic status: evidence from the Multi-Ethnic Study of Atherosclerosis (MESA). Environ Health Perspect 121(11–12):1325–1333

Han L, Zhou W, Li W, Qian Y (2018) Urbanization strategy and environmental changes: An insight with relationship between population change and fine particulate pollution. Sci Total Environ 642:789–799

Han W, Li Z, Guo J, Su T, Chen T, Wei J, Cribb M (2020) The Urban-Rural Heterogeneity of Air Pollution in 35 Metropolitan Regions across China. Remote Sensing 12(14):2320

He J, Chen W (2018) 2017 China Cancer Registry Annual Report. People's Health Publishing House Press, Beijing ((**in Chinese**))

Hong XC, Wang GY, Liu J, Song L, Wu ET (2021) Modeling the impact of soundscape drivers on perceived birdsongs in urban forests. J Clean Product 292:125315

Hu K, Guo Y, Hochrainer-Stigler S, Liu W, See L, Yang X, Zhong J, Fei F, Chen F, Zhang Y, Zhao Q, Chen G, Chen Q, Zhang Y, Ye T, Ma L, Li S, Qi J (2019) Evidence for Urban-Rural Disparity in Temperature-Mortality Relationships in Zhejiang Province, China. Environ Health Perspect 127(3):037001

Hu K, Guo Y, Yang X, Zhong J, Fei F, Chen F, Zhao Q, Zhang Y, Chen G, Chen Q, Ye T, Li S, Qi J (2019b) Temperature variability and mortality in rural and urban areas in Zhejiang province, China: An application of a spatiotemporal index. Sci Total Environ 647:1044–1051

Huang G, Zhou W, Qian Y, Fisher B (2019) Breathing the same air? Socioeconomic disparities in PM2. 5 exposure and the potential benefits from air filtration. Sci Total Environ 657:619–626

International Agency for Research on Cancer (2016a) IARC Working Group on the Evaluation of Carcinogenic Risks to Humans, IARC Monographs Volume 109: Outdoor Air Pollution

International Agency for Research on Cancer (2016b) IARC Working Group on the Evaluation of Carcinogenic Risks to Humans, IARC Monographs Volume 44: Alcohol Drinking

International Agency for Research on Cancer (2016c) IARC Working Group on the Evaluation of Carcinogenic Risks to Humans, IARC Monographs Volume 83: Tobacco Smoke and Involuntary Smoking

International Agency for Research on Cancer (2019) IARC Working Group on the Evaluation of Carcinogenic Risks to Humans, IARC Monographs Volume 168: Reducing social inequalities in cancer: evidence and priorities for research

Kondo N, Kawachi I, Subramanian SV, Takeda Y, Yamagata Z (2008) Do social comparisons explain the association between income inequality and health?: Relative deprivation and perceived health among male and female Japanese individuals. Soc Sci Med 67(6):982–987

Li T, Zhang Y, Wang J, Xu D, Yin Z, Chen H, Lv Y, Luo J, Zeng Y, Liu Y, Kinney PL, Shi X (2018) All-cause mortality risk associated with long-term exposure to ambient PM2· 5 in China: a cohort study. The Lancet Public Health 3(10):e470–e477

Li L, Ma J, Cheng Y, Feng L, Wang S, Yun X, Tao S (2020) Urban–rural disparity in the relationship between ambient air pollution and preterm birth. Int J Health Geogr 19(1):1–15

Lin W, Xu X, Ma Z, Zhao H, Liu X, Wang Y (2012) Characteristics and recent trends of sulfur dioxide at urban, rural, and background sites in North China: Effectiveness of control measures. J Environ Sci 24(1):34–49

Lipfert FW, Wyzga RE (2019) Longitudinal relationships between lung cancer mortality rates, smoking, and ambient air quality: a comprehensive review and analysis. Crit Rev Toxicol 49(9):790–818

Liu S, Page A, Yin P, Astell-Burt T, Feng X, Liu Y, Liu J, Wang L, Zhou M (2015) Spatiotemporal variation and social determinants of suicide in China, 2006–2012: findings from a nationally representative mortality surveillance system. Psychol Med 45(15):3259–3268

Liu Y, Wang R, Grekousis G, Liu Y, Yuan Y, Li Z (2019) Neighbourhood greenness and mental wellbeing in Guangzhou, China: What are the pathways? Landscape Urban Plann 190:103602

Liu XJ, Xia SY, Yang Y, Wu JF, Zhou YN, Ren YW (2020) Spatiotemporal dynamics and impacts of socioeconomic and natural conditions on PM2. 5 in the Yangtze River Economic Belt. Environ Pollut 263:114569

Lodovici M, Bigagli E (2011) Oxidative stress and air pollution exposure. J Toxicol 2011:487074

Lorch SA, Enlow E (2016) The role of social determinants in explaining racial/ethnic disparities in perinatal outcomes. Pediatr Res 79(1):141–147

Mohai P, Pellow D, Roberts JT (2009) Environmental justice. Annu Rev Environ Resour 34:405–430

Padilla CM, Kihal-Talantikite W, Vieira VM, Rossello P, Le Nir G, Zmirou-Navier D, Deguen S (2014) Air quality and social deprivation in four French metropolitan areas—A localized spatio-temporal environmental inequality analysis. Environ Res 134:315–324

Pope CA III, Dockery DW (2006) Health effects of fine particulate air pollution: lines that connect. J Air Waste Manag Assoc 56(6):709–742

Pope CA III, Burnett RT, Thun MJ, Calle EE, Krewski D, Ito K, Thurston GD (2002) Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. JAMA 287(9):1132–1141

Power MC, Kioumourtzoglou MA, Hart JE, Okereke OI, Laden F, Weisskopf MG (2015) The relation between past exposure to fine particulate air pollution and prevalent anxiety: observational cohort study. BMJ 350:h1111

Rasmussen-Torvik LJ, De Chavez PJD, Kershaw KN, Montag SE, Knutson KL, Kim KYA, Zee PC, Carnethon MR (2016) The mediation of racial differences in hypertension by sleep characteristics: Chicago area sleep study. Am J Hypertens 29(12):1353–1357

Redmond N, Baer HJ, Hicks LS (2011) Health behaviors and racial disparity in blood pressure control in the national health and nutrition examination survey. Hypertension 57(3):383–389

Salinas-Rodríguez A, Fernández-Niño JA, Manrique-Espinoza B, Moreno-Banda GL, Sosa-Ortiz AL, Qian ZM, Lin H (2018) Exposure to ambient PM2. 5 concentrations and cognitive function among older Mexican adults. Environ Int 117:1–9

Samoli E, Stergiopoulou A, Santana P, Rodopoulou S, Mitsakou C, Dimitroulopoulou C, Bauwelinck M, Hoogh K, Costa C, Mari-DellOlmo M, Corman D, Vardoulakis S, Katsouyanni K, Consortium EH (2019) Spatial variability in air pollution exposure in relation to socioeconomic indicators in nine European metropolitan areas: A study on environmental inequality. Environ Pollut 249:345–353

Schulz AJ, Omari A, Ward M, Mentz GB, Demajo R, Sampson N, Israel BA, Reyes AG, Wilkins D (2020) Independent and joint contributions of economic, social and physical environmental characteristics to mortality in the Detroit Metropolitan Area: A study of cumulative effects and pathways. Health Place 65:102391

Schwartz S (1994) The fallacy of the ecological fallacy: the potential misuse of a concept and the consequences. Am J Public Health 84(5):819–824

Shafran-Nathan R, Yuval, Broday DM (2018) Impacts of personal mobility and diurnal concentration variability on exposure misclassification to ambient pollutants. Environ Sci Technol 52(6):3520–3526

Song L, Smith GS, Adar SD, Post WS, Guallar E, Navas-Acien A, Kaufman JD, Jones MR (2020) Ambient air pollution as a mediator in the pathway linking race/ethnicity to blood pressure elevation: The multi-ethnic study of atherosclerosis (MESA). Environ Res 180:108776

Van Donkelaar A, Martin RV, Brauer M, Boys BL (2015) Global Fine Particulate Matter Concentrations from Satellite for Long-Term Exposure 2 Assessment 3. Assessment 3(4):1–16

Van Donkelaar A, Martin RV, Brauer M, Hsu NC, Kahn RA, Levy RC, Lyapustin A, Sayer AM, Winker DM (2016) Global estimates of fine particulate matter using a combined geophysical-statistical method with information from satellites, models, and monitors. Environ Sci Technol 50(7):3762–3772

Wang Q, Kwan MP, Zhou K, Fan J, Wang Y, Zhan D (2019) The impacts of urbanization on fine particulate matter (PM2. 5) concentrations: Empirical evidence from 135 countries worldwide. Environ Pollut 247:989–998

Woodruff TJ, Parker JD, Kyle AD, Schoendorf KC (2003) Disparities in exposure to air pollution during pregnancy. Environ Health Perspect 111(7):942–946

Xu Y, Jiang S, Li R, Zhang J, Zhao J, Abbar S, González MC (2019) Unraveling environmental justice in ambient PM2.5 exposure in Beijing: A big data approach. Comput Environ Urban Syst 75:12–21

Yin P, He G, Fan M, Chiu KY, Fan M, Liu C, Xue A, Liu T, Pan Y, Mu Q, Zhou M (2017) Particulate air pollution and 611 mortality in 38 of China's largest cities: time series analysis. BMJ 356:j667

Yoo E, Rudra C, Glasgow M, Mu L (2015) Geospatial estimation of individual exposure to air pollutants: Moving from static monitoring to activity-based dynamic exposure assessment. Ann Assoc Am Geogr 105(5):915–926

Zhou M, He G, Fan M, Wang Z, Liu Y, Ma J, Ma Z, Liu J, Liu Y, Wang L, Liu Y (2015) Smog episodes, fine particulate pollution and mortality in China. Environ Res 136:396–404