Review Article on Pollutional Haze

The impact of PM2.5 on the human respiratory system

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Abstract: Recently, many researchers paid more attentions to the association between air pollution and respiratory system disease. In the past few years, levels of smog have increased throughout China resulting in the deterioration of air quality, raising worldwide concerns. PM2.5 (particles less than 2.5 micrometers in diameter) can penetrate deeply into the lung, irritate and corrode the alveolar wall, and consequently impair lung function. Hence it is important to investigate the impact of PM2.5 on the respiratory system and then to help China combat the current air pollution problems. In this review, we will discuss PM2.5 damage on human respiratory system from epidemiological, experimental and mechanism studies. At last, we recommend to the population to limit exposure to air pollution and call to the authorities to create an index of pollution related to health.

Keywords: Air pollution; PM2.5; respiratory system; China

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Background

Recently, with accelerated urban development and modernization, air pollution is worsening and its impact on human health has become a main research topic. Air pollutants include gaseous pollutants and particle matters (PM). The pathogenicity of PM is determined by their size, composition, origin, solubility and their ability to produce reactive oxygen. Studies (1) have shown that smog is generally caused by high concentrations of fine particles (particle size less than or equal to 2.5 btm, referred to as PM2.5) or aerosols. It has been found that PMs with an aerodynamic diameter smaller than 10 μm have a greater impact on human health. One group of PM identified, PM2.5, have small diameters, however large surface areas and may therefore be capable of carrying various toxic stuffs, passing through the filtration of nose hair, reaching the end of the respiratory tract with airflow and accumulate there by diffusion, damaging other parts of the body through air exchange in the lungs. What's more, adults exposed to other high levels of ambient air pollution, for example PM10 and coarse particulate, also have shown increased prevalence of respiratory disease.

Recently, a growing number of studies in toxicology, epidemiology and other related fields have demonstrated that respirable particles are closely related to the incidence of human diseases and mortality rate. The "Harvard six Cities Study", published in 1996, revealed that PM2.5 was one of the causative factors of human non-accidental death. In this study, PM2.5 was positively related to daily morality of humans, particularly the elderly (RR =1.5%, 95% CI: 1.1–1.9%) (2). The study provides evidence supporting the linear relationship between non-accidental death and PM2.5. Patients with respiratory diseases account for a large proportion of these non-accidental deaths caused by air pollution. Given that PM2.5 causes asthma, respiratory inflammation, jeopardizes lung functions and even promotes cancers, its impact on human respiratory system should not be dismissed (3-5). In this review, we will discuss PM2.5 damage on human respiratory system from epidemiological,

experimental and mechanism studies.

Epidemiological evidence of PM2.5 damage on human respiratory system

After twenty years of epidemiological studies, scientists have revealed a significant correlation between fine particle pollutants and respiratory morbidity and mortality (6). A report from the last century illustrated that increased PM concentration in the air may directly lead to an elevated morbidity and mortality of a population (7,8). In European Union countries, PM2.5 decreased the average life span by 8.6 months (9).

After investigating 29 European countries, Analitis (10) found that respiratory mortality increased by 0.58% for every 10 μg/m^3 increase of PM10. It was recently reported that the prevalence rate of respiratory diseases increased by 2.07%, while hospitalization rate raised by 8% accordingly, when the daily PM2.5 increased by 10 μg/m^3 (11,12). This study also reported that elevated air particle pollutants were directly associated with more serious symptoms of respiratory tract diseases, undermined lung function and raised morbidity and mortality of cardiopulmonary diseases. Furthermore, this correlation was more obvious in the elderly, pregnant women, adolescents, infants, patients with a history of cardiopulmonary problems and other susceptible populations (13-15).

Scientists in Canada and the US found that long-term exposure to PM2.5 significantly increased not only the chances of cardiopulmonary problems but also the mortality of lung cancers (16,17). Indeed a study conducted for 7 years (from 2000 to 2007) in the US indicated that the average life span was extended by 0.35 years for every 10 μg/m^3 decrease of PM2.5 (18).

From the American Cancer Society, Pope and coworkers (19) collected a set of data, based on 500,000 adults living in large cities. They concluded that the overall mortality and mortality of cardiopulmonary diseases as well as lung cancer increased by 4%, 6% and 8%, respectively, for every 10 μg/m^3 PM2.5 increase, after ruling out smoking, diet, drinking, occupation and other risk factors. In addition, a cohort study by the American Cancer Society tracked 1.2 million American adults for 26 years [1982–2008] and found that the mortality of lung cancer increased by 15–27% when PM2.5 air concentrations increased by 10 μg/m^3 (20). This risk was even higher among patients with chronic lung diseases. More strikingly, the results of 11 cohort studies in Europe revealed that the population hazard ratio (HR) of lung adenocarcinoma was 1.55 (95% CI: 1.05–2.29), for each increase of PM2.5 by 5 μg/m^3 (21). In 2011, after balancing smoking and other interfering factors, a study (22) of 63,520 people from 6 regions in 3 states in Japan demonstrated that a higher incidence of respiratory diseases, in particular pneumonia, were closely related to long-term exposure to particles in the air. Yadav *et al.* (23) revealed that the morbidity of asthma, influenza and acute respiratory tract infection increased notably during outbreaks of smog.

Compared with Western countries, research into the hazard of PM2.5 in China began just 10 years ago. It has been reported that PM2.5 mainly occurs in the Beijing-Tianjin-Hebei Economic Zone, the Yangtze River Delta, the Pearl River Delta region, the three northeastern provinces, the Sichuan Basin, and other densely populated areas. It has seriously affected public health both physically and emotionally.

Data from the program (http://stateair.net/web/mission/1/) which tracks daily PM2.5 concentrations on the grounds of the U.S. Embassy in Beijing in the winter months from 2010 to 2014 showed that daily PM2.5 concentrations exceeded 100 μg/m^3 for more than half of the days and reached as high as 744 μg/m^3, more than 20 times the US Environmental Protection Agency's (EPA) 24-hour standard for PM2.5 of 35 μg/m^3. Surveys in Beijing, Shanghai, Guangzhou and other areas in China (24-29) displayed a strong linear correlation between daily mortality (including non-accidental death) and PM2.5 levels. In addition, the daily mortality significantly increased with increased fine PM concentration. A meta-analysis on the current dose-response relationship of particle exposure and morbidity showed that morbidity increased by 0.38% with each increase of PM10 by 10 μg/m^3 (30). Using meta-analysis, Qian *et al.* (31) studied the epidemiological literature published between 1995 and 2003. It was concluded that for every 100 μg/m^3 increase of PM2.5, the morbidity of residents increased by 12.07%. The authors also showed that respiratory outpatient visits increased during smog outbreaks (32). Therefore, the impact of particles in the air on the human respiratory system is a worldwide issue of concern.

Experimental evidence of PM2.5 damage on the respiratory system

In animal studies, Phipps (33) exposed two groups of mice to either air or cigarette smoke for 5 weeks. After intratracheal injection of streptococcus pneumoniae, bacteria counts in mice lungs after cigarette exposure were

4 times in 24 hours and 35 times in 48 hours higher than the control group, respectively. One study in China found that air pollution could cause damage, lose and dysfunction of rat tracheal cilia, resulting in infection and a declined nonspecific immune defense, and that these mice were then prone to secondary infection (34).

In addition, many studies have focused on the impact of PM2.5 on alveolar macrophages. Jalava *et al.* collected air particles from 6 cities in Europe and cultured them with mice macrophages *in vitro* for 24 hours. The viability of alveolar macrophages decreased significantly with a PM0.2-2.5 range from 300 pg/mL to 150 g/mL. Furthermore, alveolar macrophages TNF-α expression increased with increased particle concentration (35). Renwick *et al.* carried out intratracheal instillation on rats with fine particles and ultrafine particle suspensions (125 and 500 μg per rat, respectively). A LDH cytotoxicity study indicated that the viability of alveolar macrophages was severely damaged when the fine particle concentration reached 500 μg per rat (36). In another study, alveolar macrophages were harvested by instilling PM2.5 suspension (300,750, 2,000, 5,000 μg per rat) into the trachea of Wistar rats. The results indicated that the phagocytize rate and phagocytic index were remarkably lower with increased particle concentrations (37). Additional study (38) has reported that PM2.5 significantly reduces phagocytosis of alveolar macrophages both *in vitro* and *in vivo*.

Mechanism study of PM2.5 and human respiratory system

Recently, the mechanisms of the damaging effects of PM2.5 on the respiratory system have been investigated including:

(I) Injury from free radical peroxidation: earlier studies showed that the free radicals, metal and the organic components of PM2.5 can induce free radical production to oxidize lung cells, which may be the primary cause of body injury (39-42). In 1996, Donaldson and Beswick, etc. reported that the surface itself of environmental particles can produce free radicals. In addition, that the PM2.5 surface was rich in iron, copper, zinc, manganese, and other transition elements, as well as polycyclic aromatic hydrocarbons and lipopolysaccharide, etc. These components can increase free radical production in the lung, consume antioxidant ingredients and cause oxidative stress (39). Many studies (43) have confirmed that the reactive oxygen species (ROS) generated by particles, particularly by water soluble particles, produce hydroxyl radical (• OH) by activating metals. Hydroxyl radicals are the main factor causing oxidative damage of DNA. When damaged DNA is not effectively repaired in time, it can induce teratogenesis carcinogenesis, mutagenesis and other irreversible damages. Mehta *et al.* (44) found that particles could not only damage DNA and suppress DNA repair, but could also promote the replication of damaged DNA fragments and consequently prompt carcinogenesis;

(II) Imbalanced intracellular calcium homeostasis: calcium is one of the important second messengers that mediates and regulates cell functions both physiologically and pathologically. Abnormally high calcium concentrations activates a series of inflammatory reactions, leading to inflammation and cell damage. PM2.5 induces excessive production of free radicals or ROS and decreases the antioxidant capacity of cells, resulting in the peroxidation of lipids on the cell membrane and the elevation of intracellular Ca^{2+} concentrations. In addition, increased intracellular Ca^{2+} concentrations can further elevate free radical or ROS production (45). Brown *et al.* (46) showed that it is possible that ROS-mediated regulation of intracellular Ca^{2+} concentrations may be one of the mechanisms of PM2.5-induced cell damages. Xing (47) also indicated that cell apoptosis and necrosis were related to over expression of Ca^{2+}-sensitive receptors;

(III) Inflammatory injury: it has been wildly reported that PM2.5 is related to inflammatory cytokines whereby it stimulates overexpression of a number of transcription factor genes and inflammation-related cytokine genes that cause inflammatory injury. Sigaud *et al.* (48) found that PM2.5-induced inflammation led to an increase in the number of neutrophils. Gripenbäck *et al.* (49) reported that exposure to pine dust caused an increase in the number of eosinophils, T cells and mastocytes in bronchoalveolar lavage fluid and in 2003, Gordon (50) showed that PM2.5 and its microenvironment influenced the phenotype and function of two types of alveolar macrophages. The first of these macrophages, known as M1 polarized alveolar macrophage, is primarily induced by Thl-type cytokines (IL-12, IFN-γ) and pathogens in the body and promote inflammation. The second of these

macrophages, M2 polarized alveolar macrophage, is closely related to the Th2 type cytokines (IL-4 and IL-13) and the immunomodulatory cytokine (IL-10), which primarily inhibit inflammation. It has been reported that human alveolar macrophages treated with PM2.5 express high levels of M1-associated cytokines (IL-12, IFN-γ) and low levels of M2-associated cytokines (IL-4, IL-10 and IL-13) (51-53). These results indicate that cytokines can both induce neutrophil, T cell and eosinophil migration to the lungs and other tissues, and on their own, migrate to the lung, exhibiting higher cell activities, releasing more inflammatory cytokines and chemokines. The interactions between inflammatory cells and cytokines can damage lung cells synergistically. Consequently, the mechanism of action of PM2.5 in the damage to human health remains one of the primary focuses of many current studies. Several studies have illustrated how one single component of PM2.5 can influence human health, whilst others investigated the details of how an imbalance of key inflammatory cytokines can lead to certain lung diseases. Few studies have, however, investigated the pathogenesis of PM2.5 as a whole. Integration of the fragmented information from previous studies will provide a great deal of knowledge in the understanding of the harm to human health of PM2.5.

Prevention of P M2.5 damage to the respiratory system

Understanding how PM2.5 leads to respiratory diseases will assist in preventing and diagnosing the corresponding health issues and the evolution of more effective methods and technologies for the treatment of PM2.5-induced diseases. China is currently facing severe air pollution in the transition phase of industrialization and urbanization. Less than 1% of the 500 largest cities in China can meet the air quality guidelines recommended by the World Health Organization. Seven of these cities were ranked among the ten most polluted cities in the world (54). There has been mounting concern on the part of the government and the population of China generally as to the consequences of such high levels of air pollution, which are so high as to greatly limit visibility. The high levels of pollution was related to the linearity of the health effects (55).

Consequently, controlling air pollution is an arduous and long-term task. It is therefore proposed that the following guidelines be in place to address increased PM2.5 concentrations and/or an increase in smog levels:

(I) Remain indoors, close all windows and doors and if going outside, wear a qualified mask and minimize the duration or intensity of outdoor activities;
(II) Sensitive populations (the elderly and those with pre-existing cardiopulmonary problems) should be more cautious of PM2.5 pollution and minimize outdoor PM2.5 exposure;
(III) Patients with chronic cardiopulmonary problems should increase their medication dosage and pay close attention to their health to prevent severity of their symptoms during an increase in smog;
(IV) As oxidative stress is one of the main pathogenic mechanisms of PM2.5, taking antioxidant supplements or nutritious food (for example, w-3 fatty acids in fish oil);
(V) Chinese environmental authorities could launch a "smog health index", referring to the Canadian "air quality health index" by Environment Canada (EC). Such an index may instruct members of the public to prepare early and correctly thereby minimizing the health threats of smog.

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Footnote

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References

1. Zhang XY, Sun JY, Wang YQ, et al. Factors contributing to haze and fog in China. Chin Sci Bull (Chin Ver) 2013;58:1178-87.
2. Schwartz J, Dockery DW, Neas LM. Is daily mortality associated specifically with fine particles? J Air Waste Manag Assoc 1996;46:927-39.
3. Samoli E, Analitis A, Touloumi G, et al. Estimating the exposure-response relationships between particulate matter and mortality within the APHEA multicity project. Environ Health Perspect 2005;113:88-95.

4. Ostro B, Broadwin R, Green S, et al. Fine particulate air pollution and mortality in nine California counties: results from CALFINE. Environ Health Perspect 2006;114:29-33.
5. Lewis TC, Robins TG, Dvonch JT, et al. Air pollution-associated changes in lung function among asthmatic children in Detroit. Environ Health Perspect 2005;113:1068-75.
6. Brunekreef B, Holgate ST. Air pollution and health. Lancet 2002;360:1233-42.
7. Nemery B, Hoet PH, Nemmar A. The Meuse Valley fog of 1930: an air pollution disaster. Lancet 2001;357:704-8.
8. Helfand WH, Lazarus J, Theerman P. Donora, Pennsylvania: an environmental disaster of the 20th century. Am J Public Health 2001;91:553.
9. Orru H, Maasikmets M, Lai T, et al. Health impacts of particulate matter in five major Estonian towns: main sources of exposure and local differences. Air Quality, Atmosphere & Health 2011;4:247-58.
10. Analitis A, Katsouyanni K, Dimakopoulou K, et al. Short-term effects of ambient particles on cardiovascular and respiratory mortality. Epidemiology 2006;17:230-3.
11. Zanobetti A, Franklin M, Koutrakis P, et al. Fine particulate air pollution and its components in association with cause-specific emergency admissions. Environ Health 2009;8:58.
12. Dominici F, Peng RD, Bell ML, et al, Fine particulate air pollution and hospital admission for cardiovascular and respiratory diseases. JAMA 2006;295:1127-34.
13. Huynh M, Woodruff TJ, Parker JD, et al. Relationships between air pollution and preterm birth in California. Paediatr Perinat Epidemiol 2006;20:454-61.
14. Martinelli N, Girelli D, Cigolini D, et al. Access rate to the emergency department for venous thromboembolism in relationship with coarse and fine particulate matter air pollution. PLoS One 2012;7:e34831.
15. de Oliveira BF, Ignotti E, Artaxo P, et al. Risk assessment of PM(2.5) to child residents in Brazilian Amazon region with biofuel production. Environ Health 2012;11:64.
16. Schwartz J. Harvesting and long term exposure effects in the relation between air pollution and mortality. Am J Epidemiol 2000;151:440-8.
17. Franklin M, Koutrakis P, Schwartz P. The role of particle composition on the association between PM2.5 and mortality. Epidemiology 2008;19:680-9.
18. Correia AW, Pope CA 3rd, Dockery DW, et al. Effect of air pollution control on life expectancy in the United States: an analysis of 545 U.S. counties for the period from 2000 to 2007. Epidemiology 2013;24:23-31.
19. Pope CA 3rd, Burnett RT, Thun MJ. Lung cancer, cardiop-ulmonary mortality, and long-term exposure to fine particu-late air pollution. JAMA 2002;287:1132-41.
20. Turner MC, Krewski D, Pope CA 3rd, et al. Long-term ambient fine particulate matter air pollution and lung cancer in a large cohort of never-smokers. Am J Respir Crit Care Med 2011;184:1374-81.
21. Raaschou-Nielsen O, Andersen ZJ, Beelen R, et al. Air pollution and lung cancer incidence in 17 European cohorts: prospective analyses from the European Study of Cohorts for Air Pollution Effects (ESCAPE). Lancet Oncol 2013;14:813-22.
22. Katanoda K, Sobue T, Satoh H, et al. An association between long-term exposure to ambient air pollution and mortality from lung cancer and respiratory diseases in Japan. J Epidemiol 2011;21:132-43.
23. Yadav AK, Kumar K, Kasim A, et al. Visibility and incidence of respiratory diseases during the 1998 haze episode in Brunei Darussalam. Pure and Applied Geophysics 2003;160:265-77.
24. Xu X, Gao J, Dockery DW, et al. Air pollution and daily mortality in residential areas of Beijing, China. Arch Environ Health 1994;49:216-22.
25. Huang W, Tan J, Kan H, et al. Visibility, air quality and daily mortality in Shanghai, China. Sci Total Environ 2009;407:3295-300.
26. Yang C, Peng X, Huang W, et al. A time-stratified case-crossover study of fine particulate matter air pollution and mortality in Guangzhou, China. Int Arch Occup Environ Health 2012;85:579-85.
27. Qian Z, He Q, Lin HM, et al. Association of daily cause-specific mortality with ambient particle air pollution in Wuhan, China. Environ Res 2007;105:380-9.
28. Ma Y, Chen R, Pan G, et al. Fine particulate air pollution and daily mortality in Shenyang, China. Sci Total Environ 2011;409:2473-7.
29. Wong CM, Ou CQ, Chan KP, et al. The effects of air pollution on mortality in socially deprived urban areas in Hong Kong, China. Environ Health Perspect 2008;116:1189-94.
30. Kan HD, Cheng BH. Analysis of exposure-response relationships of air particulate matter and adverse health outcomes in China. Journal of Environment and Health 2002;19:422-4.
31. Qian XL, Kan HD, Song WM, et al. Meta-analysis of association between air fine particulate matter and daily mortality. Journal of Environment and Health 2005;22:246-8.

32. Li N, Peng XW, Zhang BY, et al. Relationship between air pollutant and daily hospital visits for respiratory diseases in guangzhou: a time-series study. Journal of Environment and Health 2009;26:1077-80.
33. Phipps JC, Aronoff DM, Curtis JL, et al. Cigarette smoke exposure impairs pulmonary bacterial clearance and alveolar macrophage complement-mediated phagocytosis of Streptococcus pneumoniae. Infect Immun 2010;78:1214-20.
34. Zhou Y, Wang RQ, Zhao S, et al. Effect on cytokines and ultrastructure in rats exposed to mixed air pollutants. Journal of Shenyang Medical College 2009;11:6-12.
35. Jalava PI, Salonen RO, Pennanen AS, et al. Heterogeneities in inflammatory and cytotoxic responses of RAW 264.7 macrophage cell line to urban air coarse, fine, and ultrafine particles from six European sampling campaigns. Inhal Toxicol 2007;19:213-25.
36. Renwick LC, Brown D, Clouter A, et al. Increased inflammation and altered macrophage chemotactic responses caused by two ultrafine particle types. Occup Environ Med 2004;61:442-7.
37. Huang NH, Wang Q, Xu DQ. Immunological effect of PM2.5 on cytokine production in female Wistar rats. Biomed Environ Sci 2008;21:63-8.
38. Miyata R, van Eeden SF. The innate and adaptive immune response induced by alveolar macrophages exposed to ambient particulate matter. Toxicol Appl Pharmacol 2011;257:209-26.
39. Donaldson K, Beswick PS. Free radical activity associated with the surface of the particles: a unifying factor in determining biological activity. Toxicol Lett 1996;88:293-8.
40. Greenwell LL, Moreno T, Jones TP, et al. Particle-induced oxidative damage is ameliorated by pulmonary antioxidants. Free Radic Biol Med 2002;32:898-905.
41. Rahman I, Macnee W. Role of oxidants/antioxidants in smoking-induced lung diseases. Free Radic Biol Med 1996;21:669-81.
42. Kelly FJ. Oxidative stress: its role in air pollution and adverse health effects. Occup Environ Med 2003;60:612-6.
43. Valavanidis A, Fiotakis K, Bakeas E, et al. Electron paramagnetic resonance study of the generation of reactive oxygen species catalysed by transition metals and quinoid redox cycling by inhalable ambient particulate matter. Redox Rep 2005;10:37-51.
44. Mehta M, Chen LC, Gordon T, et al. Particulate matter inhibits DNA repair and enhances mutagenesis. Mutat Res 2008;657:116-21.
45. Kim YK, Jung JS, Lee SH, et al. Effects of antioxidants and Ca2+ in cisplatin-induced cell injury in rabbit renal cortical slices. Toxicol Appl Pharmacol 1997;146:261-9.
46. Brown DM, Donaldson K, Borm PJ, et al. Calcium and ROS-mediated activation of transcription factors and TNF-acytokine gene expression in macrophages exposed to ultrafine particles. Am J Physiol Lung Cell Mol Physiol 2004;286:L344-53.
47. Xing WJ, Kong FJ, Li GW, et al. Calcium-sensing receptors induce apoptosis during simulated ischaemia-reperfusion in Buffalo rat liver cells. Clin Exp Pharmacol Physiol 2011;38:605-12.
48. Sigaud S, Goldsmith CA, Zhou H, et al. Air pollution particles diminish bacterial clearance in the primed lungs of mice. Toxicol Appl Pharmacol 2007;223:1-9.
49. Gripenbäck S, Lundgren L, Eklund A, et al. Accumulation of eosinophils and T-lymphocytes in the lungs after exposure to pinewood dust. Eur Respir J 2005;25:118-24.
50. Gordon S. Alternative activation of macrophages. Nat Rev Immunol 2003;3:23-35.
51. He M, Ichinose T, Yoshida S, et al. Urban particulate matter in Beijing, China, enhances allergen-induced murine lung eosinophilia. Inhal Toxicol 2010;22:709-18.
52. Park EJ, Roh J, Kim Y, et al. PM 2.5 collected in a residential area induced Th1-type inflammatory responses with oxidative stress in mice. Environ Res 2011;111:348-55.
53. Yoshizaki K, Brito JM, Toledo AC, et al. Subchronic effects of nasally instilled diesel exhaust particulates on the nasal and airway epithelia in mice. Inhal Toxicol 2010;22:610-7.
54. Asian-Development-Bank, 2013. Toward an Environmentally Sustainable Future: Country Environmental Analysis of the People's Republic of China. Available online: http://www. Adb.Org/publications/toward-environmentally-sustainable-future-countryenvironmental-analysis-prc
55. Aunan K, Pan XC. Exposure-response functions for health effects of ambient air pollution applicable for China -- a meta-analysis. Sci Total Environ 2004;329:3-16.

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