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Air pollution and temperature are associated with increased COVID-19 incidence: A time series study

He Li[a,1], Xiao-Long Xu[b,1], Da-Wei Dai[c,1], Zhen-Yu Huang[c,1], Zhuang Ma[a], Yan-Jun Guan[d,*]

[a] Department of Respiratory and Critical Care Medicine, General Hospital of Northern Theater Command, 83 Wen Hua Rd, Shenyang 110801, Liaoning, China
[b] Department of Neurosurgery, Shanghai Chang Hai Hospital Affiliated to China Second Military Medical University, 168 Chang Hai Rd, Shanghai 200433, China
[c] Department of Neurosurgery, Shanghai Chang Zheng Hospital Affiliated to China Second Military Medical University, 415 Feng Yang Rd, Shanghai 200003, China
[d] Department of Otorhinolaryngology, Shanghai Rui-Jin Hospital, Shanghai Jiaotong University School of Medicine, 149 Chong Qing Rd, Shanghai 200020, China

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ABSTRACT

Objectives: Although COVID-19 is known to be caused by human-to-human transmission, it remains largely unclear whether ambient air pollutants and meteorological parameters could promote its transmission.

Methods: A retrospective study was conducted to study whether air quality index (AQI), four ambient air pollutants ($PM_{2.5}$, PM_{10}, NO_2 and CO) and five meteorological variables (daily temperature, highest temperature, lowest temperature, temperature difference and sunshine duration) could increase COVID-19 incidence in Wuhan and XiaoGan between Jan 26th to Feb 29th in 2020.

Results: First, a significant correlation was found between COVID-19 incidence and AQI in both Wuhan ($R^2 = 0.13$, $p < 0.05$) and XiaoGan ($R^2 = 0.223$, $p < 0.01$). Specifically, among four pollutants, COVID-19 incidence was prominently correlated with $PM_{2.5}$ and NO_2 in both cities. In Wuhan, the tightest correlation was observed between NO_2 and COVID-19 incidence ($R^2 = 0.329$, $p < 0.01$). In XiaoGan, in addition to the $PM_{2.5}$ ($R^2 = 0.117$, $p < 0.01$) and NO_2 ($R^2 = 0.015$, $p < 0.05$), a notable correlation was also observed between the PM_{10} and COVID-19 incidence ($R^2 = 0.105$, $p < 0.05$). Moreover, temperature is the only meteorological parameter that constantly correlated well with COVID-19 incidence in both Wuhan and XiaoGan, but in an inverse correlation ($p < 0.05$).

Conclusions: AQI, $PM_{2.5}$, NO_2, and temperature are four variables that could promote the sustained transmission of COVID-19.

Introduction

The outbreak of COVID-19 from Wuhan, China, was officially characterized as a pandemic on March 11th, 2020 (World Health Organization, 2020b), which has led to more than 3.5 million subjected infected and 0.24 million dead worldwide as of May 4th, 2020 (World Health Organization, 2020a). The causative pathogen of COVID-19 has been confirmed as the severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2) (Lu et al., 2020), which belongs to the coronavirus family and previously caused severe acute respiratory syndrome (SARS) (Peiris et al., 2004) and the Middle East respiratory syndrome (MERS) (Zaki et al., 2012).

Air pollution has been an on-going research focus as it is a major environmental threat to human health. Sufficient evidence has tightly linked ambient air pollution to occurrence of numerous respiratory diseases, such as COPD (Ling and van Eeden, 2009) and asthma (Gorai et al., 2016). Moreover, air pollution is also associated with infectious diseases transmission. For example, worse air quality has also been shown to increase SARS fatality (Cui et al., 2003) as well as to increase influenza incidence (Landguth et al., 2020). In laboratory conditions, van Doremalen et al. (2020) demonstrated a long viability of SARS-CoV-2 in ambient aerosols, which could be an important source of COVID-19 transmission (Luo et al., 2020). However, whether ambient air pollutants are associated with increased incidence of COVID-19 in realistic situations remains largely unknown.

* Corresponding author.
E-mail address: guanyjsigma@yeah.net (Y.-J. Guan).
[1] These authors contributed equally to this work.

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Previous study indicated that meteorological parameters can affect spread and thriving of multiple viruses. For example, ambient temperature and relative humidity are inversely associated with influenza A infection rate in Japan (Iha et al., 2016). The coronavirus also exhibited a seasonal oscillation of outbreak, which also suggested a strong association between meteorological parameters and virus transmission and viability (Killerby et al., 2018). Moreover, although the epidemiological characteristics of SARS-CoV-2 are not clear, a recent study predicted SARS-CoV-2 transmits more efficiently in winter than summer (Lipsitch, 2020), indicating the importance of temperature in COVID-19 transmission. However, whether COVID-19 transmission is associated with meteorological parameters, at this moment, is not backed by sufficient investigations and robust evidence.

In this retrospective study, we attempted to conduct an exploratory analysis looking at the association between environment conditions (including ambient pollutants and meteoroidal parameter) and COVID-19 incidence/mortality in Wuhan, given a city-wide lockdown and varying pollution/meteorological data throughout the entire study period.

Materials and methods

COVID-19 incidence data

In this time-series analysis, COVID-19 incidence counts in Wuhan and XiaoGan were provided by the Centers for Disease Control and Prevention (CDC) of Hubei Province (Health Commission of the Hubei Province, 2020). The data used in this study are daily case counts of positive diagnoses of COVID-19 from all reporting sources, including laboratory and clinical diagnoses. COVID-19 cases of all ages are included. In total, the COVID-19 incidence data for Wuhan produced over 35 'clusters' of time series between Jan 26th to Feb 29th in 2020.

Environmental condition data

The daily air quality index (AQI), $PM_{2.5}$, PM_{10}, NO_2 and CO concentration were retrieved from the Platform AQI (Platform AQI, 2020). Five meteorological parameters were retrieved from the database of Weather.com (The Weather Channel, 2020), including daily mean temperature, highest temperature, lowest temperature, sunrise and sunset time. Daily temperature difference and sunshine duration were calculated based on the difference of highest and lowest temperature and sunrise and sunset time, respectively. Thus, a total of five meteorological parameters were enrolled as independent variables.

Data analysis

Due to imperfect daily reporting practices, COVID-19 incidence numbers in XiaoGan exhibited data on Feb 19th which was −15. Furthermore, China updated their diagnostic criteria on Feb 12th and 13th, which resulted in a significant increase of COVID-19 incidence cases on these days (Han and Yang, 2020). Thus, these data were excluded from the current study.

All data analyses were done in GraphPad Prism® 8.0 (GraphPad Software, La Jolla, CA, USA). First, a descriptive analysis was performed to provide an overview of COVID-19 incidence and air quality during the study period. Next, we utilized a linear regression model to fit the dependent variables (COVID-19 incidence) for each independent variable (four ambient air pollutants and five meteorological parameters). As SARS-CoV-2 has a median incubation period of 4 days in humans (Guan et al., 2020), all independent variables were used to fit daily COVID-19 incidence from 4 days later. The statistical tests were two-sided, and p-value <0.05 was considered as statistically significant.

Table 1
An overview of air quality index (AQI), ambient air pollution and meteorological parameters between Jan 26th to Feb 29th in 2020 in Wuhan and XiaoGan, China.

	Wuhan		XiaoGan	
	Mean	Std. deviation	Mean	Std. deviation
Air quality index (AQI)	63.63	25.30	71.58	27.83
Ambient air pollutants				
$PM_{2.5}$ ($\mu g/m^3$)	44.16	21.63	50.39	24.18
PM_{10} ($\mu g/m^3$)	51.88	22.26	59.65	25.98
NO_2 ($\mu g/m^3$)	21.47	7.66	11.35	3.95
CO ($\mu g/m^3$)	0.88	0.04	1.16	0.04
Meteorological parameters				
Temperature (°C)	7.19	4.04	7.26	3.92
Daily highest temp (°C)	13.25	4.19	12.97	4.96
Daily lowest temp (°C)	4.38	4.55	4.87	3.91
Daily temp diff (°C)	8.81	3.76	7.97	3.85
Sunshine duration (h)	11.04	0.28	10.91	0.27

Table 2
The correlation between COVID-19 incidence and three ambient air pollutants along with five meteorological parameters, Jan 26th to Feb 29th in 2020 in Wuhan and XiaoGan, China. The data marked with *, ** and *** indicated statistical significance, where $p < 0.05$, 0.01 and 0.001, respectively.

	Wuhan		XiaoGan	
	Slope	R^2	Slope	R^2
Air quality index (AQI)	0.015 ± 0.007*	0.127	0.133 ± 0.046**	0.222
Ambient air pollutants				
$PM_{2.5}$	0.015 ± 0.006*	0.174	0.117 ± 0.046**	0.23
PM_{10}	0.117 ± 0.006	0.105	0.105 ± 0.044*	0.158
NO_2	0.007 ± 0.002***	0.329	0.015 ± 0.007*	0.158
CO	0.000 ± 0.000**	0.203	−0.000 + 0.000	0.022
Meteorological data				
Temperature	−0.002 ± 0.001*	0.126	−0.014 ± 0.007*	0.13
Daily highest temp	−0.002 ± 0.001	0.114	−0.014 ± 0.009	0.076
Daily lowest temp	−0.003 ± 0.001*	0.143	−0.013 ± 0.007	0.109
Daily temp diff	0.000 ± 0.001	0.003	−0.001 ± 0.007	0.001
Sunshine duration	−0.000 ± 0.000	0.000	−0.002 ± 0.000***	0.407

Results

Detailed information of daily COVID-19 incidence number was listed in Table 1, including the AQI, four ambient air pollutants and five meteorological parameters. The AQI values for Wuhan and XiaoGan were 63.63 ± 4.47 and 71.58 ± 5, respectively, both of which were categorized as moderate according to the US EPA standard (United States Environmental Protection Agency, 2019a). The highest and lowest daily COVID-19 incidences were 1690 cases on Feb 16th and 80 cases on Jan 26th in Wuhan, respectively. Meanwhile, incidences in XiaoGan were 424 on Feb 5th and 0 on Feb 29th.

We then looked into the correlation between local AQI and COVID-19 incidence number in each city (Table 2, Figure 1). The data showed that AQI was significantly and positively associated with daily COVID-19 incidence number in both Wuhan ($R^2 = 0.13$, $p < 0.05$) and XiaoGan ($R^2 = 0.223$, $p < 0.01$), which indicated the important role of AQI in COVID-19 transmission. Thus, we further studied the association of daily newly diagnosed COVID-19 cases with each air pollutant in Wuhan (Table 2, Figure 2). Interestingly, all ambient air pollutants showed positive association with daily COVID-19 incidence. Among them, NO_2 ($R^2 = 0.329$, $p < 0.01$), $PM_{2.5}$ ($R^2 = 0.174$, $p < 0.05$) and CO ($R^2 = 0.203$, $p < 0.001$) exhibited statistical significance. Next, we studied the correlation between meteorological parameters and COVID-19 incidence in Wuhan. Among five parameters, daily temperature ($R^2 = 0.126$, $p < 0.05$) and daily lowest temperature ($R^2 = 0.143$, $p < 0.05$) were predominantly correlated with COVID-19 incidence, but both in an inverse correlation.

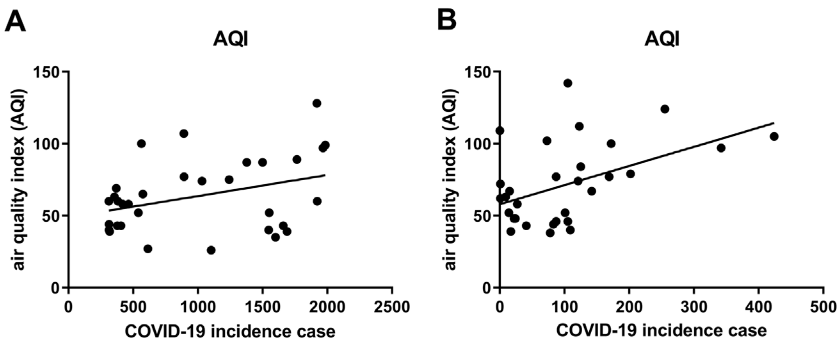

Figure 1. The correlation between daily COVID-19 incidence and air quality index (AQI) in Wuhan (A) and XiaoGan (B).

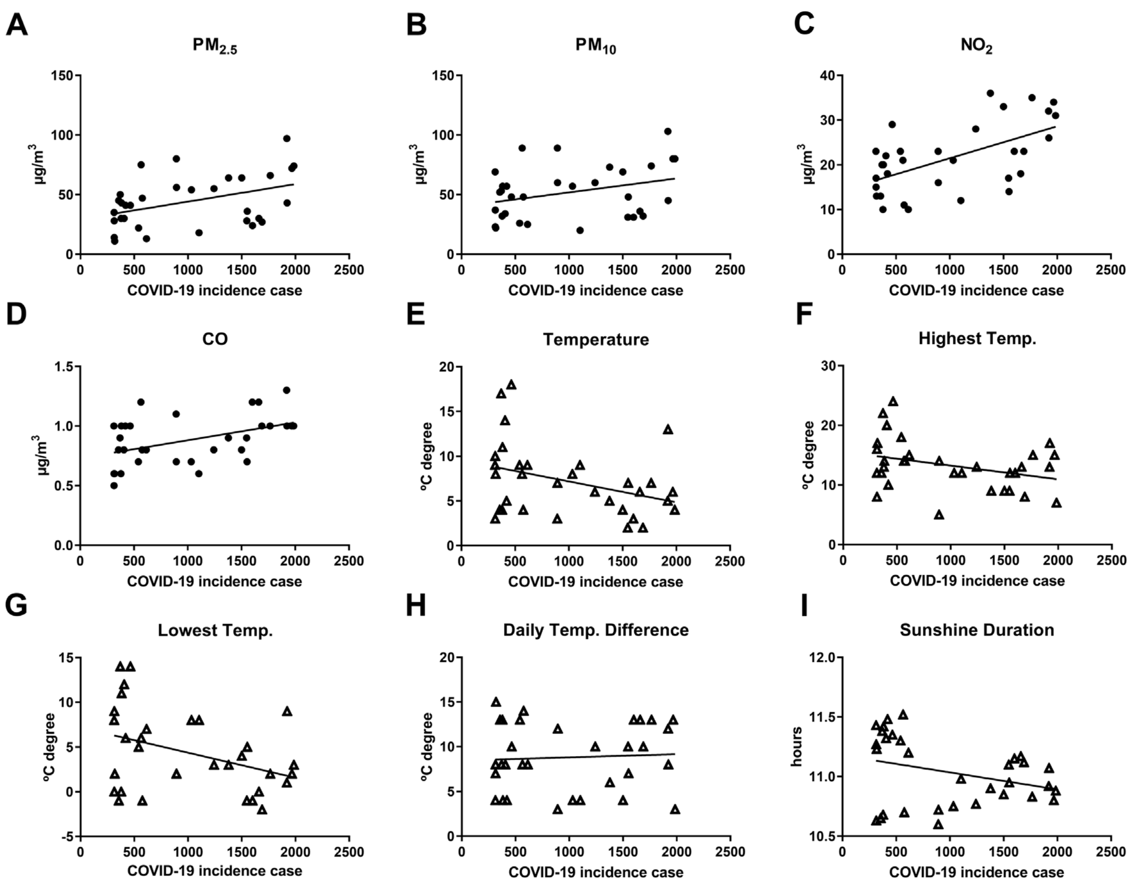

Figure 2. The correlation between daily COVID-19 incidence and ambient air pollution/five meteorological parameters in Wuhan.

In XiaoGan, both $PM_{2.5}$ ($R^2 = 0.23$, $p < 0.01$) and NO_2 ($R^2 = 0.158$, $p < 0.05$) were also apparently associated with COVID-19 incidence. Moreover, a notable correlation was also observed between the PM_{10} and incidence cases ($R^2 = 0.158$, $p < 0.05$). Among five meteorological factors, COVID-19 incidence correlated well with the temperature ($R^2 = 0.13$, $p < 0.05$) and daily sunshine duration ($R^2 = 0.407$, $p < 0.01$), which were, however, in an inverse correlation (Figure 3).

Discussion

Multiple factors could impact viral transmission. For example, influenza viability and activity could be potentiated by ambient air pollutants and some meteorological variables (Iha et al., 2016; Landguth et al., 2020). However, this has not been examined for the SARS-CoV-2. Thus, a preliminary analysis was conducted in the current study to assess the role of air pollution and meteorological parameters on COVID-19 transmission. We found that COVID-19 incidence was enhanced by increased AQI (decreased air quality), $PM_{2.5}$, and NO_2 and weakened by temperature.

The PM is hazardous due to its complicate composition and strong capacity of air suspension. PM could be divided into coarse and fine particulate matter, whose diameters are less than 10 μm and 2.5 μm, respectively. Among various causes of respiratory illness, the PM has been shown to potentiate viral transmissions. For instance, ambient $PM_{2.5}$ concentration was prominently correlated with influenza-like illness risk during the flu season in Beijing, China (Feng et al., 2016). In a single hospital setting, researchers found that both influenza and respiratory syncytial virus remain airborne for a long time period after they attach to PM, which allows viruses to be transmitted by the airborne route (Lindsley et al., 2010). Additionally, viral replication in the

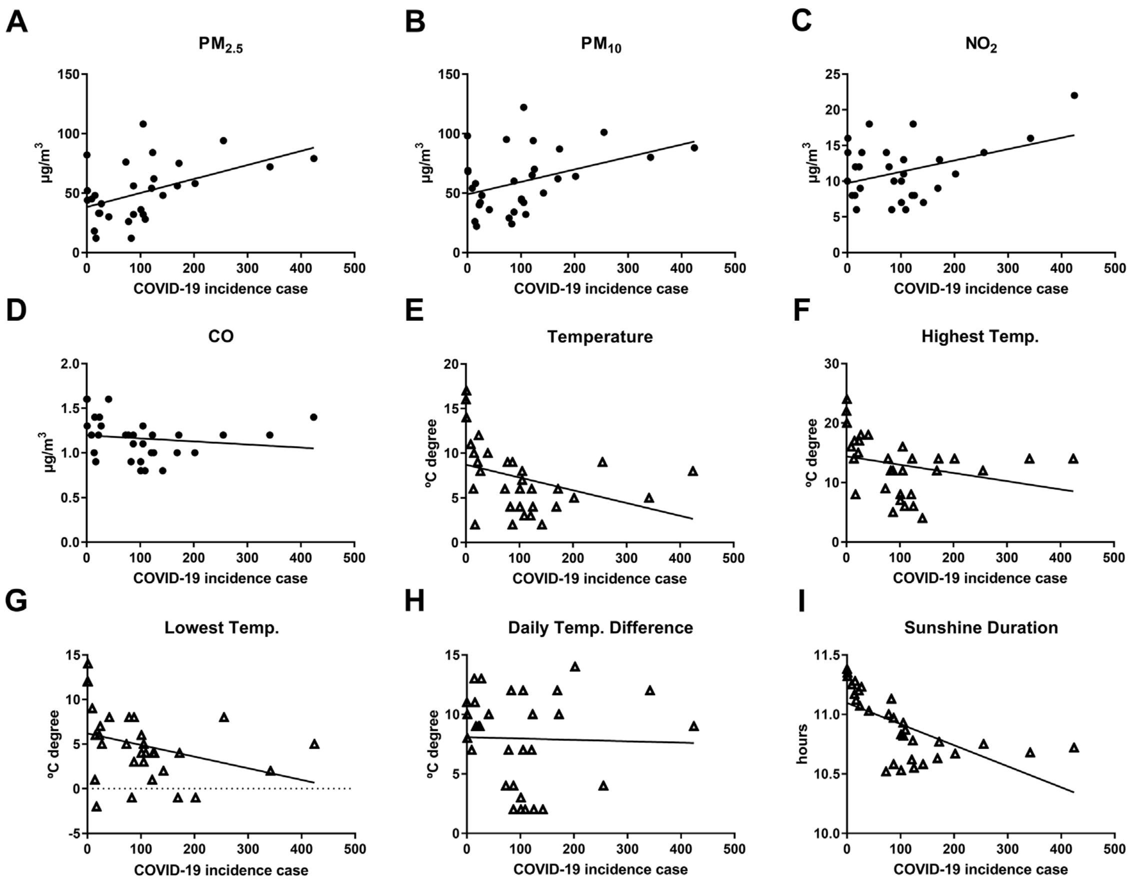

Figure 3. The correlation between daily COVID-19 incidence and ambient air pollution/five meteorological parameters in XiaoGan.

respiratory system is enhanced by the negative effect of PM on the human respiratory barrier integrity (Xian et al., 2020; Zhao et al., 2018). However, it remains particularly unclear whether the ambient air pollutant could assist SARS-CoV-2 transmission. In the current study, the $PM_{2.5}$ concentration is correlated with the COVID-19 incidence in a positive correlation, which agreed with previous studies. Based on this information, we hypothesize that PM could potentiate the transmission ability of SARS-CoV-2 in two ways: (1) $PM_{2.5}$ could disrupt the integrity of the human respiratory barrier integrity (Zhao et al., 2018). Thus, the dysfunctional respiratory barriers are more likely to expose deeper respiratory tissue to foreign pathogens. (2) PM could form condensation nuclei for viral attachment (Lee et al., 2014). Due to its relatively smaller size, $PM_{2.5}$ is more pernicious as it can penetrate the respiratory tract and reach alveoli directly (Tellier, 2009). Since both PMs, especially $PM_{2.5}$ concentration, were constantly higher than safety guidelines of the US EPA (United States Environmental Protection Agency, 2019b) in both cities, we believed that $PM_{2.5}$ is a stronger factor promoting SARS-CoV-2 transmission.

A number of studies demonstrate the adverse health effects of NO_2 exposure. For example, short-term increase of outdoor NO_2 concentration can significantly increase the risk of upper respiratory tract infection (Li et al., 2018). This phenomenon was particularly notable in children, as this subpopulation is highly susceptible to NO_2 induced lung injury (Ghosh et al., 2012; Lin et al., 2013; Moshammer et al., 2006). Viral infection was common after NO_2 exposure. According to Chauhan et al. (2003), four viruses were frequently detected in NO_2-related respiratory tract infection, and coronavirus was one of them. Previous study indicated that preceding NO_2 exposure can decrease host immunity and thus significantly increase infection risk of cytomegalovirus in mice (Rose et al., 1988). Moreover, recovered mice tended to be re-infected after re-exposing to NO_2 (Rose et al., 1989). In the current study, although the NO_2 level was constantly lower than the US EPA standards (United States Environmental Protection Agency, 2016), our data revealed that COVID-19 incidence was highly correlated with the ambient NO_2 concentration. This finding agreed with epidemiological studies from other regions of the world (Chauhan et al., 2003; Lin et al., 2013).

So far, epidemiological studies identified at least nine virus categories that are capable of infecting the respiratory tract (Nichols et al., 2008; Pavia, 2011). Although all feature seasonal oscillation of outbreaks, only three viruses show peak incidences in the winter months, which are the Influenza, human coronavirus, and human respiratory syncytial virus (Killerby et al., 2018; Midgley et al., 2007). Although the epidemiological characteristics of SARS-CoV-2 are not clear, recent study predicted that SARS-CoV-2 transmits more efficiently in winter than summer (Lipstich, 2020), indicating the importance of temperature. These data agreed with our results as temperature seems to decrease the incidence of COVID-19, indicating an inhibitory effect of temperature on SARS-CoV-2 transmission. This phenomenon might be related to life-style as people tend to huddle indoors together during the winter season. Future study needs to investigate the direct effect of temperature on viral activity as well.

Other than the PM and NO_2, the data from Wuhan also indicated that CO has a strong positive effect on SARS-CoV-2 transmission. However, the data from XiaoGan failed to repeat the same result. So far, only a few studies are available concerning the effect of CO on viral transmission. For example, Su et al. (2019) presented that CO can increase the risk of influenza-like illness. Ali also identified that CO had a weak positive association with influenza transmissibility (Ali et al., 2018). We believe our current results could not fully represent the potency of CO on SARS-CoV-2 transmission due to relatively limited study period and location. Thus, we cannot conclude the effect of CO on SARS-CoV-2 transmission based on current data. Further studies are required to elaborate on this issue.

The current study has some limitations. First, there are only two cities enrolled, which might result in some results deviation from the exact effect of ambient pollution and meteorological parameters on SARS-CoV-2 transmission. Second, the study period is relatively short compared to other epidemiological study. In future study, we will enroll more data from multiple countries and areas to validate the results from current study.

In conclusion, we found that AQI, $PM_{2.5}$, NO_2 and temperature are four variables that could potential promote the sustained transmission of SARS-CoV-2. Personal protective devices, especially the facial mask, shall be suggested to residents for coronavirus protection in highly polluted regions.

Conflict of interest

There is no conflict of interest in this study.

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Ethical approval

The current study has been approved by the ethics committee of Shanghai Rui-Jin Hospital.

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References

Ali S, Wu P, Cauchemez S, He D, Fang V, Cowling B, et al. Ambient ozone and influenza transmissibility in Hong Kong. Eur Respir J 2018;51(5):1800369.
Chauhan A, Inskip H, Linaker C, Smith S, Schreiber J, Johnston S, et al. Personal exposure to nitrogen dioxide (NO_2) and the severity of virus-induced asthma in children. Lancet 2003;361(9373):1939–44.
Cui Y, Zhang Z, Froines J, Zhao J, Wang H, Yu S, et al. Air pollution and case fatality of SARS in the People's Republic of China: an ecologic study. Environ Health 2003;2(1):15.
Feng C, Li J, Sun W, Zhang Y, Wang Q. Impact of ambient fine particulate matter (PM2.5) exposure on the risk of influenza-like-illness: a time-series analysis in Beijing, China. Environ Health 2016;15:17.
Ghosh R, Joad J, Benes I, Dostal M, Sram RJ, Hertz-Picciotto I. Ambient nitrogen oxides exposure and early childhood respiratory illnesses. Environ Int 2012;39(1):96–102.
Gorai A, Tchounwou P, Tuluri F. Association between Ambient air pollution and asthma prevalence in different population groups residing in eastern Texas, USA. Int J Environ Res Public Health 2016;13(4):378.
Guan W-J, Ni Z-Y, Hu Y, Liang W-H, Ou C-Q, He J-X, et al. Clinical characteristics of coronavirus disease 2019 in China. N Engl J Med 2020;, doi:http://dx.doi.org/10.1056/NEJMoa2002032.
Han Y, Yang H. The transmission and diagnosis of 2019 novel coronavirus infection disease (COVID-19): a Chinese perspective. J Med Virol 2020;.
Health Commission of the Hubei Province. The real time corona virus epidemiological situation of Hubei province. 2020 Available from: http://wjw.hubei.gov.cn/bmdt/ztzl/fkxxgzbdgrfyyq/index.shtml.
Iha Y, Kinjo T, Parrott G, Higa F, Mori H, Fujita J. Comparative epidemiology of influenza A and B viral infection in a subtropical region: a 7-year surveillance in Okinawa, Japan. BMC Infect Dis 2016;16(1):650.
Killerby M, Biggs H, Haynes A, Dahl R, Mustaquim D, Gerber S, et al. Human coronavirus circulation in the United States 2014–2017. J Clin Virol 2018;101:52–6.
Landguth E, Holden Z, Graham J, Stark B, Mokhtari E, Kaleczyc E, et al. The delayed effect of wildfire season particulate matter on subsequent influenza season in a mountain west region of the USA. Environ Int 2020;139:105668.
Lee G, Saravia J, You D, Shrestha B, Jaligama S, Hebert V, et al. Exposure to combustion generated environmentally persistent free radicals enhances severity of influenza virus infection. Part Fibre Toxicol 2014;11:57.
Li Y, Xiao C, Li J, Tang J, Geng X, Cui L, et al. Association between air pollution and upper respiratory tract infection in hospital outpatients aged 0–14 years in Hefei, China: a time series study. Public Health 2018;156:92–100.
Lin Y, Chang C, Chang S, Chen P, Lin C, Wang Y. Temperature, nitrogen dioxide, circulating respiratory viruses and acute upper respiratory infections among children in Taipei, Taiwan: a population-based study. Environ Res 2013;120:109–18.
Lindsley W, Blachere F, Davis K, Pearce T, Fisher M, Khakoo R, et al. Distribution of airborne influenza virus and respiratory syncytial virus in an urgent care medical clinic. Clin Infect Dis 2010;50(5):693–8.
Ling S, van Eeden S. Particulate matter air pollution exposure: role in the development and exacerbation of chronic obstructive pulmonary disease. Int J Chronic Obstr Pulm Dis 2009;4:233–43.
Lipsitch M. Seasonality of SARS-CoV-2: will COVID-19 go away on its own in warmer weather?. 2020 Available from: https://ccdd.hsph.harvard.edu/will-covid-19-go-away-on-its-own-in-warmer-weather/.
Lu R, Zhao X, Li J, Niu P, Yang B, Wu H, et al. Genomic characterisation and epidemiology of 2019 novel coronavirus: implications for virus origins and receptor binding. Lancet 2020;395(10224):565–74.
Luo C, Yao L, Zhang L, Yao M, Chen X, Wang Q, et al. Possible transmission of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) in a public bath center in Huai'an, Jiangsu Province, China. JAMA Netw Open 2020;3(3):e204583.
Midgley C, Haynes A, Baumgardner J, Chommanard C, Demas S, Prill M, et al. Determining the seasonality of respiratory syncytial virus in the United States: the impact of Increased molecular testing. J Infect Dis 2007;216:345–55.
Moshammer H, Hutter H, Hauck H, Neuberger M. Low levels of air pollution induce changes of lung function in a panel of schoolchildren. Eur Respir J 2006;27:1138–43.
Nichols W, Campbell A, Boeckh M. Respiratory viruses other than influenza virus: impact and therapeutic advances. Clin Microbiol Rev 2008;21(2):274–90.
Pavia A. Viral infections of the lower respiratory tract: old viruses, new viruses, and the role of diagnosis. Clin Infect Dis 2011;52(Suppl. 4):S284–9.
Peiris J, Guan Y, Yuen K. Severe acute respiratory syndrome. Nat Med 2004;10(12 Suppl):S88–97.
Platform AQI. Online air quality monitoring and analysis platform. 2020 Available from: https://www.aqistudy.cn/.
Rose R, Fuglestad J, Skornik W, Hammer S, Wolfthal S, Beck B, et al. The pathophysiology of enhanced susceptibility to murine cytomegalovirus respiratory infection during short-term exposure to 5 ppm nitrogen dioxide. Am Rev Respir Dis 1988;137:912–7.
Rose R, Pinkston P, Skornik W. Altered susceptibility to viral respiratory infection during short-term exposure to nitrogen dioxide. Research Report 24. Health Effects Institute; 1989. p. 1–24.
Su W, Wu X, Geng X, Zhao X, Liu Q, Liu T. The short-term effects of air pollutants on influenza-like illness in Jinan, China. BMC Public Health 2019;19(1):1319.
Tellier R. Aerosol transmission of influenza A virus: a review of new studies. J R Soc Interface 2009;6(Suppl. 6):S783–90.
The Weather Channel. Wuhan, Hubei, People's Republic of China monthly weather. 2020 Available from: https://weather.com/weather/monthly/l/2637660151899903e8cbdd23636051470b6731863286ec74b3033421c-b87e1e8.
United States Environmental Protection Agency. NAAQS table. 2016 Available from: https://www.epa.gov/criteria-air-pollutants/naaqs-table.
United States Environmental Protection Agency. Understanding the AQI. 2019 Available from: https://cfpub.epa.gov/airnow/index.cfm?action=aqibasics.aqi.
United States Environmental Protection Agency. What are the air quality standards for PM?. 2019 Available from: https://www3.epa.gov/region1/airquality/pm-aq-standards.html.
van Doremalen N, Bushmaker T, Morris DH, Holbrook MG, Gamble A, Williamson BN, et al. Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. N Engl J Med 2020;382(16):1564–7.
World Health Organization. Coronavirus disease (COVID-19) outbreak situation. 2020 Available from: https://www.who.int/emergencies/diseases/novel-coronavirus-2019.
World Health Organization. Situation Report – 51. Coronavirus disease 2019 (COVID-19). 2020.
Xian M, Ma S, Wang K, Lou H, Wang Y, Zhang L, et al. Particulate matter 2.5 causes deficiency in barrier integrity in human nasal epithelial cells. Allergy Asthma Immunol Res 2020;12(1):56–71.
Zaki A, van Boheemen S, Bestebroer T, Osterhaus A, Fouchier R. Isolation of a novel coronavirus from a man with pneumonia in Saudi Arabia. N Engl J Med 2012;367(19):1814–20.
Zhao R, Guo Z, Zhang R, Deng C, Xu J, Dong W, et al. Nasal epithelial barrier disruption by particulate matter ≤ 2.5 μm via tight junction protein degradation. J Appl Toxicol 2018;38(5):678–87.