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Air Pollution Mediates the Association between Human Mobility and COVID-19 Infection

Kang Lo[1+], Nguyen Thanh Tung[2,3+], Chih-Da Wu[4,5], Huynh Nguyen Xuan Thao[6], Hoang Ba Dung[3], Tran Phan Chung Thuy[7], Hsiao-Chi Chuang[8,9,10*]

[1] Institute of Environmental and Occupational Health Sciences, College of Public Health, National Taiwan University, Taipei, Taiwan
[2] International Ph.D. Program in Medicine, College of Medicine, Taipei Medical University, Taipei, Taiwan
[3] Otorhinolaryngology Department, Cho Ray Hospital, Ho Chi Minh City, Vietnam
[4] Department of Geomatics, National Cheng Kung University, Tainan, Taiwan
[5] National Institute of Environmental Health Sciences, National Health Research Institutes, Miaoli, Taiwan
[6] Otorhinolaryngology Department, Ho Chi Minh City University of Medicine and Pharmacy, Ho Chi Minh City, Vietnam
[7] Otorhinolaryngology Department, Faculty of Medicine, Vietnam National University Ho Chi Minh City, Ho Chi Minh City, Vietnam
[8] Division of Pulmonary Medicine, Department of Internal Medicine, Shuang Ho Hospital, Taipei Medical University, New Taipei City, Taiwan
[9] School of Respiratory Therapy, College of Medicine, Taipei Medical University, Taipei, Taiwan
[10] Cell Physiology and Molecular Image Research Center, Wan Fang Hospital, Taipei Medical University, Taipei, Taiwan

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*** Corresponding Author:**
chuanghc@tmu.edu.tw

† These authors contributed equally to this work

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ABSTRACT

The effects of the restriction policies on human mobility and on the prevention of SARS-CoV-2 (coronavirus disease 2019 (COVID-19) transmission were reported. The efficiency of human mobility restriction due to the social distancing measures of cities on preventing SARS-CoV-2 spread remains unclear. The objective of this study was to investigate the mediating effects of air pollution on the association between human mobility and daily confirmed COVID-19 cases. Daily mobility data (i.e., walking, driving, and using public transport), air pollutants, and confirmed COVID-19 cases were collected in Taiwan during 1 to 30 May 2021. Associations of air pollution with 7-day-lag confirmed COVID-19 cases and with mobility were examined by linear regression models, while the mediating effects were assessed using a PROCESS analysis. We observed that an increase in air pollution was associated with an increase in confirmed COVID-19 cases ($p < 0.05$). We found that 1 min spent on mobility was associated with changes in air pollution levels ($p < 0.05$). We observed that levels of particulate matter with an aerodynamic diameter of < 10 μm (PM_{10}), $PM_{2.5}$, NO_2, and CO mediated associations of walking, driving, and using public transport with confirmed COVID-19 cases ($p < 0.05$). Our findings suggest that the nationwide restrictions (social distancing measures) may reduce human mobility and activities, which was associated with a decrease in confirmed COVID-19 cases due to the mediating effects of air pollution. Reductions in human mobility and air pollution could be effective measures for controlling COVID-19 transmission.

Keywords: COVID-19, Air pollution, Particulate matter, Restriction, SARS-CoV-2, Transmission

1 INTRODUCTION

Since the primary outbreak of coronavirus disease 2019 (COVID-19) in Wuhan, China in late

2019, the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has spread worldwide and infected over 200 million people (WHO, 2021). There are approximately 211 million confirmed cases and 4.4 million deaths due to COVID-19 infection according to a World Health Organization (WHO) report (WHO, 2021). Despite most patients having a mild respiratory illness after an infection, about 26% of patients experience severe pulmonary abnormalities (Huang *et al.*, 2020). Besides the association of COVID-19 transmissibility with human mobility, as evaluated in previous studies, it is worth mentioning that emerging evidence has shown the impact of air pollution on transmission of COVID-19 (Cao *et al.*, 2021; Shao *et al.*, 2021). Most countries implemented national restrictions to avoid the exponential growth of hospital admissions and to progressively slow down COVID-19 transmission (Flaxman *et al.*, 2020). National lockdowns successfully reduced human activities and air pollution levels (Sahraei *et al.*, 2021). However, the emergence of mutant SARS-CoV-2 variants from the United Kingdom (UK) and South Africa led to unexpected resurgences in the pandemic around the world in 2021.

The alpha variant (B.1.1.7 lineage) of SARS-CoV-2 spread to Taiwan and caused a severe threat to public health in early May 2021 (Taiwan CDC, 2021a). Additionally, the low vaccination rate (8.35%) also was a potential risk for virus transmission (Taiwan CDC, 2021a). To prevent rapid SARS-CoV-2 transmission in Taiwan, the Taiwan Central Epidemic Command Center (CECC) announced a Level 3 national restriction on 19 May 2021 (Taiwan CECC, 2021c). Restrictions included prohibition of outdoor gatherings of more than 10 people, reductions of unnecessary mobility and activities, and the closure of entertainment venues (i.e., cinemas, museums, galleries, and sport centers) and educational facilities (i.e., libraries, schools, colleges, and universities) (Taiwan CECC, 2021b). However, the efficiency of the reduction in human mobility due to the social distancing measures of cities on preventing SARS-CoV-2 transmission remains unclear. We hypothesized that air pollution mediated the association between mobility and confirmed COVID-19 cases. The objective of this study was to examine the effects of the reduction in human mobility on daily confirmed COVID-19 cases in Taiwan and the mediating effects of air pollution.

2 METHODS

2.1 Data of COVID-19 Cases and Human Mobility

Daily confirmed COVID-19 case data (1–30 May 2021) in each city of Taiwan were obtained from the National Center for High-Performance Computing (https://scidm.nchc.org.tw). Daily mobility data in each city of Taiwan during the same period were collected from the Mobility Trends Reports (https://covid19.apple.com/mobility). Mobility data included walking, driving, and using public transport. Residential cities for confirmed cases were matched with commuter zones to access their mobility, and daily residential mobility is expressed as average minutes in transit.

2.2 Air Pollution

Town-level exposure to air pollution (i.e., particulate matter (PM) of < 10 μm in aerodynamic diameter (PM_{10}), $PM_{2.5}$, nitrogen dioxide (NO_2), and carbon monoxide (CO)) from 1 to 23 May 2021 was estimated using the hybrid kriging/land-use regression (LUR) method (Wu *et al.*, 2018; Chen *et al.*, 2020). Air pollution data were obtained from Taiwan Environmental Protection Administration air quality monitoring stations (https://airtw.epa.gov.tw/). Land-use predictors with a Spearman's correlation coefficient of ≥ 0.4 with effects on air pollution were entered into a stepwise linear regression. Moreover, a set of pollutant levels was created by a leave-one-out kriging interpolation method and added to the model to improve its robustness.

2.3 Statistical Analysis

We examined associations of air pollution with 7-day-lag 6611 confirmed COVID-19 cases and with human mobility using linear regression models. Next, the mediating effects of air pollution on the association of mobility with confirmed COVID-19 cases were estimated using the PROCESS (Hayes, 2013). The direct effect was defined as the effect of mobility on confirmed COVID-19 cases after controlling for the indirect (mediated) effects of air pollution. The indirect effect was defined as the effect of mobility on confirmed COVID-19 cases through the mediating effect of air pollution.

The total effect was determined as the indirect effect plus the direct effect. Co-variables of age and sex were adjusted in the linear regression and mediating analyses. Results of the linear regression are presented as beta (β) coefficients and 95% confidence intervals (CIs). Results of the mediation effect are presented as beta coefficients, standard errors, and 95% CIs. Data analyses were conducted using SPSS ver. 20.0 (SPSS, Chicago, IL, USA). Values of $p \leq 0.05$ were accepted as statistically significant.

3 RESULTS AND DISCUSSION

3.1 Human Mobility and Daily Confirmed COVID-19 Cases

During the study period, we observed that mobility through walking, driving, and using public transport gradually decreased by 37.76%, 37.87%, and 65.42%, respectively. Our results showed that mobility reductions began from 7 May, which was before the nationwide restrictions on 19 May. This could have been due to public awareness of the beginning of COVID-19 infections in the community. Thus, people began to work from home and to reduce their outdoor activities before the official restriction announcement in Taiwan. There were 6611 confirmed COVID-19 cases in total during the study period. We observed that the number of COVID-19 cases increased steadily to the highest number of 699 cases on 22 May, then the confirmed cases gradually decreased after 27 May 2021 (Fig. 1). Increasing numbers of recent studies have investigated associations between mobility restrictions and declines in confirmed COVID-19 cases (Wang *et al.*, 2020a; Nouvellet *et al.*, 2021). Our findings suggest a trend between human mobility and confirmed COVID-19 cases. Therefore, we performed further analysis to examine the direct effects of human mobility on confirmed COVID-19 cases in Table 3.

3.2 Air Pollution was Associated with Increases in Confirmed COVID-19 Cases

Table 1 depicted the minimum, maximum, and average concentrations of air pollution during the study period. We observed a decline in air pollutant levels after the nationwide restrictions on 19 May. Notably, concentrations of PM_{10}, $PM_{2.5}$, NO_2, and CO respectively decreased by 42%, 37%, 35%, and 25%. We next examined the 7-day-lag effects of confirmed COVID-19 cases on air

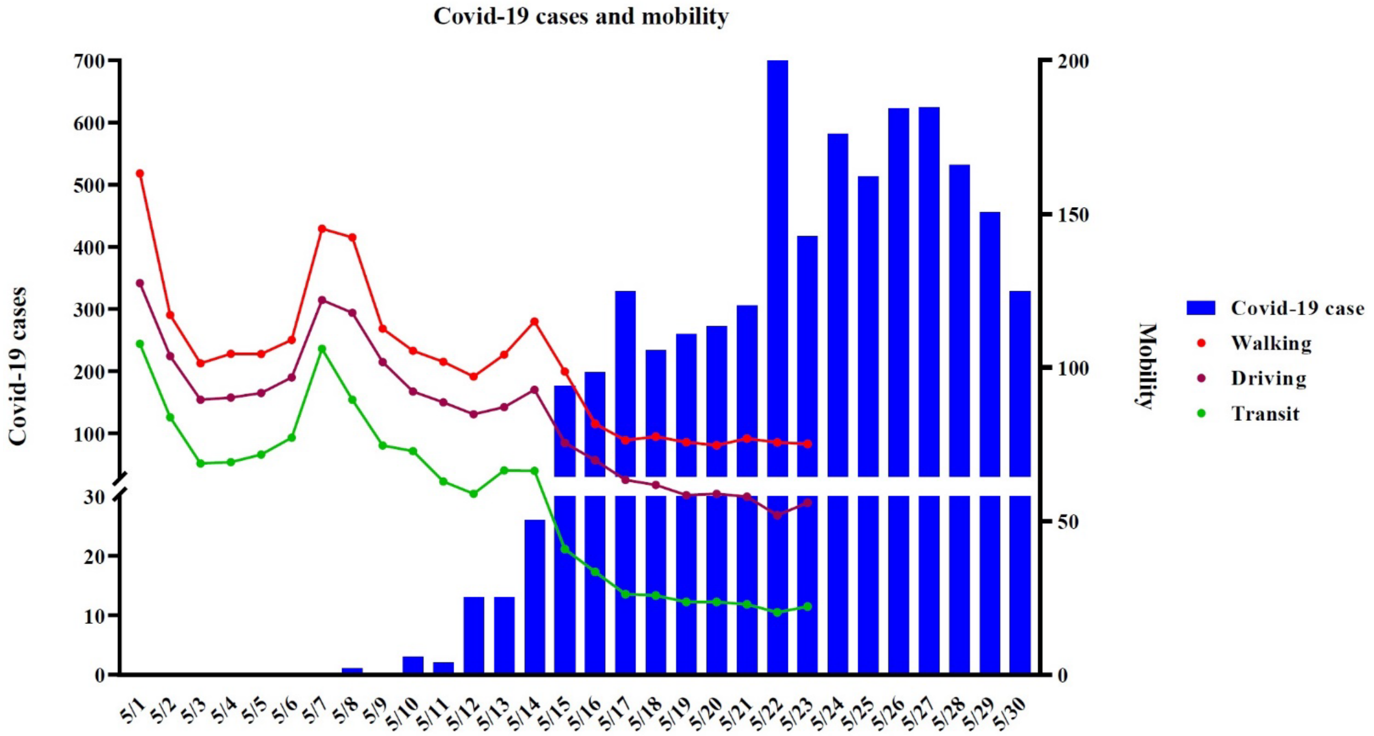

Fig. 1. Daily distributions of human mobility and COVID-19 confirmed cases during 1 to 30 May 2021 in Taiwan.

Table 1. Associations between ambient air pollution exposure and adjusted 7-day-lag COVID-19 cases (*N* = 6611).

Air pollution	Minimum concentration	Min-date	Maximum concentration	Max-date	Average concentration	COVID-19 cases	
						β coefficient	95% CI
PM_{10} (μg m^{-3})	0.01	3-May-21	73.67	4-May-21	17.25	0.042*	0.036, 0.048
$PM_{2.5}$ (μg m^{-3})	2.11	24-May-21	42.11	3-May-21	11.34	0.025*	0.011, 0.039
NO_2 (ppb)	0.46	19-May-21	27.79	1-May-21	5.84	0.077*	0.067, 0.086
CO (ppb)	0.12	16-May-21	0.73	7-May-21	0.21	2.650*	2.280, 3.020

Notes: CI, confidence interval; min-date, the date with the lowest concentration of particular air pollutant in the study period; max-date, the date with the highest concentration of particular air pollutant in the study period; ppb, parts per billion; PM_{10}, particulate matter with an aerodynamic diameter of ≤ 10 μm; $PM_{2.5}$, particulate matter with an aerodynamic diameter of ≤ 2.5 μm; NO_2, nitrogen dioxide; CO, carbon monoxide.
Models were adjusted for age and sex.
* $p < 0.05$.

pollution. The 7-day lag effect on the newly confirmed COVID-19 cases and mortality was reported in previous studies (Wang *et al.*, 2020a; Chung and Chan, 2021; Dales *et al.*, 2021). Previous findings showed that 10 μg m^{-3} increase in $PM_{2.5}$ was associated with the confirmed cases of COVID-19, and the estimated strongest relative risk were observed at 7-day lag (Wang *et al.*, 2020a). We observed that 1-unit increases in PM_{10}, $PM_{2.5}$, NO_2, and CO were respectively associated with 0.042 (95% CI: 0.036, 0.048), 0.025 (95% CI: 0.011, 0.039), 0.077 (95% CI: 0.067, 0.086), and 2.650 (95% CI: 2.280, 3.020) increases in confirmed COVID-19 cases (Table 1). The association between air pollution exposure and COVID-19 cases was identified in various countries. For instance, a multi-city study in China showed that both single-day and cumulative lag effects of short-term exposure to $PM_{2.5}$ and PM_{10} were associated with an increased risk of COVID-19 infection (Wang *et al.*, 2020a). Another study suggested that exposure to short-term NO_2 was positively associated with the transmissibility of COVID-19 in China (Yao *et al.*, 2021). A previous report showed that short-term exposure to PM_{10}, $PM_{2.5}$, NO_2, and O_3 was associated with increases in daily COVID-19 infections (Zhu *et al.*, 2020a). Furthermore, a study in the United States found that daily ozone (O_3) concentrations were associated with new confirmed cases of COVID-19 (Adhikari and Yin, 2020). These results are consistent with our findings that exposure to air pollution might increase the risk of confirmed COVID-19 cases.

3.3 Human Mobility Reduction was Associated with Declines in Air Pollution

Associations of population mobility with the three commuting modes and levels of ambient air pollution are shown in Table 2. We found that 1 min spent walking, driving, and using public transport was respectively associated with 0.051 (95% CI: 0.044, 0.059), 0.107 (95% CI: 0.095, 0.118), and 0.107 (95% CI: 0.096, 0.117) unit increases in PM_{10}. We observed that 1 min spent walking, driving, and using public transport was respectively associated with a –0.010 (95% CI: –0.013, –0.006) unit decrease, a 0.023 (95% CI: 0.018, 0.029) unit increase, and a 0.045 (95% CI: 0.040, 0.049) unit increase in $PM_{2.5}$. We found that 1 min spent walking, driving, and using public transport was respectively associated with 0.024 (95% CI: 0.019, 0.029), 0.060 (95% CI: 0.052, 0.067), and 0.082 (95% CI: 0.076, 0.089) unit increases in NO_2. Finally, we observed that 1 min spent walking, driving, and using public transport was respectively associated with 0.000 (95% CI: 0.000, 0.000), 0.001 (95% CI: 0.000, 0.001), and 0.001 (95% CI: 0.001, 0.002) unit increases in CO. These results indicated that individuals commuting by driving or public transport were associated with higher levels of PM_{10}, $PM_{2.5}$, NO_2, and CO than were those commuting by walking. The effects of human mobility on air pollutants (expressed by beta coefficients) decreased as follows: $PM_{10} > NO_2 > PM_{2.5} >$ CO. Our results suggest that a restriction in human mobility was associated with declines in air pollution levels, which was in line with previous studies (Archer *et al.*, 2020; Zhu *et al.*, 2020b). It was reported that social restriction policies are able to reduce human mobility for disease control (Bonaccorsi *et al.*, 2020; Wang *et al.*, 2020b). A previous study in India showed that approximately 50% decreases in PM_{10}, $PM_{2.5}$, and NO_2 levels and a 30% decrease in CO levels occurred in Delhi City during the lockdown period compared to the pre-lockdown period (Mahato *et al.*, 2020). Another study in Europe found that lockdown measures led to

Table 2. Changes in ambient air pollution for different categories of mobility (*N* = 6611).

Variable	β coefficient	95% CI
PM_{10}		
Walking	0.051*	0.044, 0.059
Driving	0.107*	0.095, 0.118
Using public transport	0.107*	0.096, 0.117
$PM_{2.5}$		
Walking	-0.010*	–0.013, –0.006
Driving	0.023*	0.018, 0.029
Using public transport	0.045*	0.040, 0.049
NO_2		
Walking	0.024*	0.019, 0.029
Driving	0.060*	0.052, 0.067
Using public transport	0.082*	0.076, 0.089
CO		
Walking	0.000*	0.000, 0.000
Driving	0.001*	0.000, 0.001
Using public transport	0.001*	0.001, 0.002

Notes: CI, confidence interval; PM_{10}, particulate matter with an aerodynamic diameter of $\leq 10\ \mu m$; $PM_{2.5}$, particulate matter with an aerodynamic diameter of $\leq 2.5\ \mu m$; NO_2, nitrogen dioxide; CO, carbon monoxide.

Models were adjusted for age and sex.

* $p < 0.05$.

significant declines in PM_{10}, $PM_{2.5}$, and NO_2 levels (Menut *et al.*, 2020). Together, mobility restrictions by social distancing policies were associated with air pollution declines.

3.4 Air Pollution Mediated Associations between Mobility and Confirmed COVID-19 Cases

Next, we examined the mediating effects of air pollutants on the association between mobility and confirmed COVID-19 cases as shown in Table 3. In terms of total effects, we observed that 1 min spent walking, driving, and using public transport was respectively associated with –0.244 (95% CI: –0.327, –0.161), –0.131 (95% CI: –0.167, –0.095), and –0.061 (95% CI: –0.083, –0.040) decreases in confirmed COVID-19 cases. We found that the direct effects of walking, driving, and using public transport on confirmed COVID-19 cases after controlling for the indirect (mediated) effects were statistically significant ($p < 0.05$). In terms of indirect (mediated) effects, we observed that 1 min spent walking, through the mediating effects of PM_{10} and NO_2, was respectively associated with 0.109 (95% CI: 0.092, 0.131) and 0.087 (95% CI: 0.065, 0.113) increases in COVID-19 cases. However, 1 min spent walking, through the mediating effects of $PM_{2.5}$ and CO, was respectively associated with -0.009 (95% CI: –0.013, –0.004) and -0.017 (95% CI: –0.035, –0.004) decreases in confirmed COVID-19 cases. We found that 1 min spent driving, through the mediating effects of PM_{10}, $PM_{2.5}$, NO_2, and CO, was respectively associated with 0.084 (95% CI: 0.072, 0.099), 0.011 (95% CI: 0.008, 0.017), 0.083 (95% CI: 0.067, 0.099), and 0.028 (95% CI: 0.018, 0.038) increases in confirmed COVID-19 cases. Next, we observed that 1 min spent using public transport, through the mediating effects of PM_{10}, $PM_{2.5}$, NO_2, and CO, was respectively associated with 0.056 (95% CI: 0.048, 0.066), 0.018 (95% CI: 0.012, 0.024), 0.085 (95% CI: 0.074, 0.096), and 0.047 (95% CI: 0.039, 0.054) increases in COVID-19 cases. Importantly, we found that beta coefficients of indirect effects were higher than those of direct effects and total effects. This finding suggests the mediating effects of air pollution on the association between human mobility and confirmed COVID-19 cases. Particulate matter could be another transmission mode of SARS-CoV-2 in the atmosphere. A previous study reported the mediating effects of air pollution on the relationship between the intra-city migration index and COVID-19 infections (Zhu *et al.*, 2020b). It was also demonstrated that exposure to air pollution increased the risk of the COVID-19 mortality (Coker *et al.*, 2020; Lolli *et al.*, 2020). These results show that air pollution plays an essential mediating role in terms

Table 3. Total, direct, and indirect effects of changes in mobility (walking, driving, and using public transport) with 7-day-lag confirmed COVID-19 cases on the basis of ambient air pollution exposure (*N* = 6611).

Variable	β coefficient	Standard error	LLCI	ULCI
Walking				
PM$_{10}$				
Total	–0.244*	0.035	–0.327	–0.161
Direct	–0.353*	0.035	–0.419	–0.288
Indirect	0.109*	0.092	0.092	0.131
PM$_{2.5}$				
Total	–0.244*	0.035	–0.327	–0.161
Direct	–0.236*	0.035	–0.301	–0.170
Indirect	–0.009*	0.004	–0.013	–0.004
NO$_2$				
Total	–0.244*	0.035	–0.327	–0.161
Direct	–0.332*	0.031	–0.397	–0.266
Indirect	0.087*	0.013	0.065	0.113
CO				
Total	–0.244*	0.035	–0.327	–0.161
Direct	–0.227*	0.031	–0.288	–0.161
Indirect	–0.017*	0.009	–0.035	–0.004
Driving				
PM$_{10}$				
Total	–0.131*	0.018	–0.167	–0.095
Direct	–0.216*	0.018	–0.252	–0.180
Indirect	0.084*	0.008	0.072	0.099
PM$_{2.5}$				
Total	–0.131*	0.018	–0.167	–0.095
Direct	–0.142*	0.018	–0.179	–0.107
Indirect	0.011*	0.003	0.008	0.017
NO$_2$				
Total	–0.131*	0.018	–0.167	–0.095
Direct	–0.213*	0.018	–0.249	–0.177
Indirect	0.083*	0.009	0.067	0.099
CO				
Total	–0.131*	0.018	–0.167	–0.095
Direct	–0.159*	0.018	–0.194	–0.124
Indirect	0.028*	0.005	0.018	0.038
Using public transport				
PM$_{10}$				
Total	–0.061*	0.011	–0.083	–0.040
Direct	–0.118*	0.011	–0.140	–0.096
Indirect	0.056*	0.005	0.048	0.066
PM$_{2.5}$				
Total	–0.061*	0.011	–0.083	–0.040
Direct	–0.080*	0.011	–0.102	–0.056
Indirect	0.018*	0.003	0.012	0.024
NO$_2$				
Total	–0.061*	0.011	–0.083	–0.040
Direct	–0.145*	0.011	–0.168	–0.124
Indirect	0.085*	0.006	0.074	0.096
CO				
Total	–0.061*	0.011	–0.083	–0.040
Direct	–0.108*	0.011	–0.130	–0.086
Indirect	0.047*	0.004	0.039	0.054

Notes: LLCI, lower limit confidence interval; ULCI, upper limit confidence interval. PM$_{10}$, particulate matter with an aerodynamic diameter of $\leq$ 10 μm; PM$_{2.5}$, particulate matter with an aerodynamic diameter of $\leq$ 2.5 μm; NO$_2$, nitrogen dioxide; CO, carbon monoxide.

Models were adjusted for age and sex.

* $p < 0.05$.

of COVID-19 transmission. Previous reports suggest that early social restrictions could effectively control the spread of COVID-19 (Wang *et al.*, 2020b; Zhou *et al.*, 2020), which is in line with our findings. This may be due to the direct and indirect effects of air pollution on COVID-19 transmission. First, PM is considered a "carrier" for the direct transmission method of COVID-19 (Comunian *et al.*, 2020; Farhangrazi *et al.*, 2020; Bourdrel *et al.*, 2021; Tung *et al.*, 2021). Notably, a previous study in Italy found marker genes of SARS-CoV-2 (i.e., *N*, *E*, and *RdRP*) in PM_{10} samples (Setti *et al.*, 2020). Meanwhile, a study involving 10 cities in Turkey also found SARS-CoV-2 gene (*N*1 and *RdRP*) expressions in ambient PM (Kayalar *et al.*, 2021). Another study reported the presence of SARS-CoV-2 RNA in $PM_{2.5}$ samples collected from hospital wards (Nor *et al.*, 2021). Second, previous *in vivo* studies found that exposure to $PM_{2.5}$ resulted in increased expressions of transmembrane protease serine type 2 (TMPRSS2) and angiotensin-converting enzyme 2 (ACE2) in lung tissues, which are essential factors facilitating entry of SARS-CoV-2 into host cells (Chuang *et al.*, 2020; Li *et al.*, 2021; Sagawa *et al.*, 2021). Therefore, a reduction in air pollution levels caused by restrictions on human mobility could have resulted in declines in confirmed COVID-19 cases in our study. Taken together, our findings implied that reductions in human mobility (i.e., walking, driving, and using public transport) by restriction policies may be associated with declines in COVID-19 infections through the mediating effects of air pollution.

4 CONCLUSION

To conclude, our findings demonstrated that human mobility restrictions caused by the nationwide restrictions could have resulted in decreases in confirmed COVID-19 cases through the mediating effects of air pollution. Therefore, reductions in human mobility and the consequent declines in air pollution could be effective measures for controlling spread of the COVID-19 pandemic.

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DISCLAIMER

The authors declare that they have no conflicts of interest.

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