JAMA | Original Investigation

Association of Public Health Interventions With the Epidemiology of the COVID-19 Outbreak in Wuhan, China

An Pan, PhD; Li Liu, MD, PhD; Chaolong Wang, PhD; Huan Guo, MD, PhD; Xingjie Hao, PhD; Qi Wang, MD, PhD; Jiao Huang, PhD; Na He, PhD; Hongjie Yu, PhD; Xihong Lin, PhD; Sheng Wei, MD, PhD; Tangchun Wu, MD, PhD

IMPORTANCE Coronavirus disease 2019 (COVID-19) has become a pandemic, and it is unknown whether a combination of public health interventions can improve control of the outbreak.

OBJECTIVE To evaluate the association of public health interventions with the epidemiological features of the COVID-19 outbreak in Wuhan by 5 periods according to key events and interventions.

DESIGN, SETTING, AND PARTICIPANTS In this cohort study, individual-level data on 32 583 laboratory-confirmed COVID-19 cases reported between December 8, 2019, and March 8, 2020, were extracted from the municipal Notifiable Disease Report System, including patients' age, sex, residential location, occupation, and severity classification.

EXPOSURES Nonpharmaceutical public health interventions including *cordons sanitaire*, traffic restriction, social distancing, home confinement, centralized quarantine, and universal symptom survey.

MAIN OUTCOMES AND MEASURES Rates of laboratory-confirmed COVID-19 infections (defined as the number of cases per day per million people), across age, sex, and geographic locations were calculated across 5 periods: December 8 to January 9 (no intervention), January 10 to 22 (massive human movement due to the Chinese New Year holiday), January 23 to February 1 (*cordons sanitaire*, traffic restriction and home quarantine), February 2 to 16 (centralized quarantine and treatment), and February 17 to March 8 (universal symptom survey). The effective reproduction number of SARS-CoV-2 (an indicator of secondary transmission) was also calculated over the periods.

RESULTS Among 32 583 laboratory-confirmed COVID-19 cases, the median patient age was 56.7 years (range, 0-103; interquartile range, 43.4-66.8) and 16 817 (51.6%) were women. The daily confirmed case rate peaked in the third period and declined afterward across geographic regions and sex and age groups, except for children and adolescents, whose rate of confirmed cases continued to increase. The daily confirmed case rate over the whole period in local health care workers (130.5 per million people [95% CI, 123.9-137.2]) was higher than that in the general population (41.5 per million people [95% CI, 41.0-41.9]). The proportion of severe and critical cases decreased from 53.1% to 10.3% over the 5 periods. The severity risk increased with age: compared with those aged 20 to 39 years (proportion of severe and critical cases, 12.1%), elderly people (≥80 years) had a higher risk of having severe or critical disease (proportion, 41.3%; risk ratio, 3.61 [95% CI, 3.31-3.95]) while younger people (<20 years) had a lower risk (proportion, 4.1%; risk ratio, 0.47 [95% CI, 0.31-0.70]). The effective reproduction number fluctuated above 3.0 before January 26, decreased to below 1.0 after February 6, and decreased further to less than 0.3 after March 1.

CONCLUSIONS AND RELEVANCE A series of multifaceted public health interventions was temporally associated with improved control of the COVID-19 outbreak in Wuhan, China. These findings may inform public health policy in other countries and regions.

JAMA. 2020;323(19):1915-1923. doi:10.1001/jama.2020.6130
Published online April 10, 2020.

Editorial page 1908

Supplemental content

Author Affiliations: Author affiliations are listed at the end of this article.

Corresponding Authors: Tangchun Wu, MD, PhD (wut@tjmu.edu.cn), and Sheng Wei, MD, PhD (shengwei@hust.edu.cn), School of Public Health, Tongji Medical College, Huazhong University of Science and Technology, 13 Hongkong Rd, Wuhan 430030, Hubei, China; and Xihong Lin, PhD, Department of Biostatistics, Harvard T.H. Chan School of Public Health, 665 Huntington Ave, Boston, MA 02115 (xlin@hsph.harvard.edu).

Coronavirus disease 2019 (COVID-19) is an emerging respiratory infectious disease caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), which was first detected in early December 2019 in Wuhan, China. As of April 6, 2020, COVID-19 had quickly spread to the majority of countries worldwide, affected more than 1.1 million individuals, and caused nearly 63 000 deaths.[1] Although studies have described the clinical characteristics of patients with COVID-19,[2-7] and a previous study has reported the early transmission dynamics of the first 425 confirmed cases in Wuhan,[8] more recent data are required to illustrate the full spectrum of the epidemiological characteristics of the outbreak in the epicenter.

Several modeling studies have used the international cases exported from Wuhan to extrapolate the severity of the epidemic,[9-13] estimating that the Wuhan travel ban delayed the epidemic progression by 3 to 5 days in mainland China,[12,13] while reducing case importations to other countries by nearly 80% through mid-February.[12] However, to our knowledge, no study has yet comprehensively evaluated the association of various public health interventions implemented by the Chinese government (including but not limited to intensive intracity and intercity traffic restriction, social distancing measures, home isolation and centralized quarantine, and improvement of medical resources; **Figure 1**) with outbreak control within Wuhan city.

In this study, the epidemiological characteristics of patients with COVID-19 in Wuhan through March 8, 2020, were described, and the rate of confirmed cases and effective reproduction number in different periods according to key events and interventions were compared to evaluate the temporal associations of multiple public health interventions with control of the COVID-19 outbreak in Wuhan.

Key Points

Question Was there an association of public health interventions with improved control of the COVID-19 outbreak in Wuhan, China?

Findings In this cohort study that included 32 583 patients with laboratory-confirmed COVID-19 in Wuhan from December 8, 2019, through March 8, 2020, the institution of interventions including *cordons sanitaire*, traffic restriction, social distancing, home quarantine, centralized quarantine, and universal symptom survey was temporally associated with reduced effective reproduction number of SARS-CoV-2 (secondary transmission) and the number of confirmed cases per day across age groups, sex, and geographic regions.

Meaning A series of multifaceted public health interventions was temporally associated with improved control of the COVID-19 outbreak in Wuhan and may inform public health policy in other countries and regions.

Methods

Source of Data

Characteristics of patients with COVID-19 from December 2019 through March 8, 2020, were extracted on March 9 from the municipal Notifiable Disease Report System, including birth date, sex, occupation, residential district, date of symptom onset (the self-reported date of symptoms such as fever, cough, or other respiratory symptoms), and date of confirmed diagnosis (the laboratory confirmation date of SARS-CoV-2 infection in the biosamples). A case was recorded as a health care worker if the patient reported working in a hospital or clinic. Waiver of informed consent for collection of epidemiological data from patients with COVID-19 was granted by the National Health Commission of China as part of the infectious disease outbreak investigation. All identifiable personal information was removed for privacy protection.

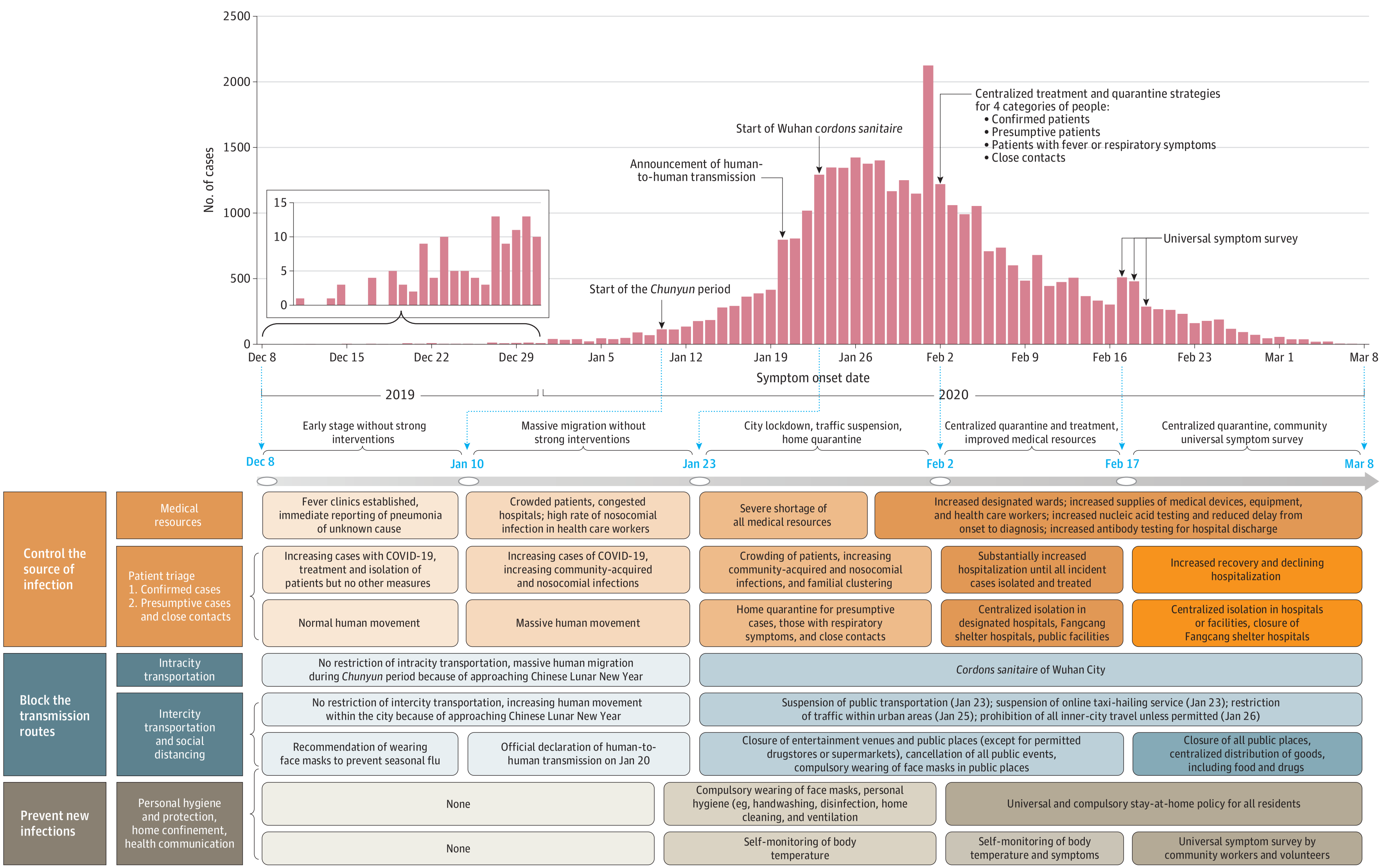
Case Definitions

Cases were diagnosed and the severity status was categorized as mild, moderate, severe, or critical according to the Diagnosis and Treatment Scheme for COVID-19 released by the National Health Commission of China (details in the eMethods in the Supplement).[14] A laboratory-confirmed case was defined if the patient had a positive result for SARS-CoV-2 virus by real-time reverse transcriptase-polymerase chain reaction (RT-PCR) assay or high-throughput sequencing of nasal and pharyngeal swab specimens. Only laboratory-confirmed cases were included in primary analyses for the consistency of case definition throughout the periods. There were an additional 17 365 cases of clinically diagnosed COVID-19 (ie, by symptom report and chest x-ray but without a positive RT-PCR result) in the data set. However, only clinically diagnosed cases were permitted for case tracking from February 9 through February 19, when testing became more broadly available, and only permitted for presumptive cases in Hubei Province. Furthermore, many of the cases were actually not new, but previous cases for which retrospective diagnoses were made based on medical records. Therefore, we only included laboratory-confirmed cases in our analyses for the consistency of case definition throughout the periods, as well as to be comparable to data in other areas outside Hubei Province. Consequently, the number of cases in the primary analysis was smaller than the officially reported number, although clinically diagnosed cases were included in a sensitivity analysis (outlined below).

Classification of 5 Time Periods

To better reflect the dynamics of the COVID-19 epidemic and corresponding interventions, 5 periods were classified based on important dates that could affect the virus transmission in Wuhan (Figure 1). The time before January 10, 2020, the first date of *Chunyun* (massive migration for the Chinese Lunar New Year), was considered as the first period, when no COVID-19–specific interventions were imposed. The second period was the *Chunyun* of January 10 to 22, 2020, when massive population movement occurred and was expected to accelerate the spread of COVID-19.[15] No strong intervention was imposed during the *Chunyun* period; the first announcement of human-to-human transmission and infections in health care workers was made on January 20. During this period, hospitals started to be overcrowded with patients with fever or respiratory symptoms.

Figure 1. The Epidemic Curve, Key Events and Features, and Public Health Interventions Across the 5 Periods During the COVID-19 Outbreak in Wuhan, China



The epidemic curve is shown as the number of incident cases each day by the symptom onset date. Details of the key events, features of the situation, and public health interventions across the 5 periods are further described in the eMethods in the Supplement. *Chunyun* is a period of significant travel in China with extremely high traffic load around the Chinese Lunar New Year. *Cordons sanitaire* restrict movement of people outside of a defined area.

During the third period, between January 23 and February 1, the local government first blocked all outbound transportation from the city and subsequently suspended public transit and banned all vehicular traffic within the city. Other social distancing measures were also implemented, including compulsory mask wearing in public places and cancellation of social gatherings. Due to a severe shortage of medical resources in this period, many confirmed or presumptive cases could not receive timely diagnosis and treatment and were self-quarantined at home. On February 2, with improvement in medical resources, the government implemented a policy of centralized quarantine and treatment of all confirmed and presumptive cases, those with fever or respiratory symptoms, and close contacts of confirmed cases in designated hospitals or facilities. Meanwhile, a stay-at-home policy was implemented for all residents in the city. On February 17, the government initiated door-to-door and individual-to-individual symptom screening for all residents with support from thousands of community workers.

Taken together, the outbreak was divided into 5 periods: no intervention before January 10, massive human migration between January 10 and 22, city lockdown with traffic suspension and home quarantine between January 23 and February 1, intensified measures with centralized quarantine and treatment between February 2 and 16, and community universal symptom survey on and after February 17, 2020. Specific events and features are shown in Figure 1.

Outcomes

Daily rate of confirmed cases, defined as the number of laboratory-confirmed cases per day per million people, were estimated by patient age, sex, health care occupation, and residential district across periods. The calculation used the number of cases in each period divided by the number of days in each period (33, 13, 10, 15, and 21 days) and the subtotal population size in each stratum from the Wuhan Statistical Yearbook 2018. The effective reproduction number R_t, defined as the mean number of secondary cases generated by a typical primary case at time t in a population, was calculated as an indicator to measure the transmission of SARS-CoV-2 both before and after the interventions. Clinical severity information was extracted from the data set and was available for 32 325 confirmed cases (258 cases had missing values and were not included in the clinical severity analyses).

Statistical Analysis

The distribution of age, sex, and occupation in laboratory-confirmed cases was described, and the epidemic curve by the symptom onset date and important dates of interventions was plotted. A sensitivity analysis was also conducted to include the clinically diagnosed cases in the epidemic curve. The geographical distributions of daily rates of COVID-19 cases across Wuhan city through the 5 periods were presented using ArcGIS software version 10.6 (Environmental Systems Research Institute Inc). A modified Poisson regression with robust variance was used to evaluate the relationship between age, sex, time period, and health care occupation with disease severity (mild and moderate vs severe and critical).[16] The 4 variables were included simultaneously and risk ratios (RRs) were reported along with 95% CIs. All statistical analyses were performed using SAS statistical software version 9.3 (SAS Institute Inc), and P values were 2-tailed with statistical significance set at .05.

The R_t was calculated using the method developed by Cori et al[17] in R version 3.6.2 (R Foundation for Statistical Computing). The daily number of reported COVID-19 cases and the serial interval (mean, 7.5 days [SD, 3.4 days]; constant across periods), derived from a previous epidemiological survey of the first 425 cases in Wuhan,[8] were used to estimate R_t and its 95% credible interval on each day via a 5-day moving average. The R_t was calculated for the whole period, but results were shown beginning with January 1, 2020, given the limited number of diagnosed cases and limited diagnosis capacity in December 2019.

Results

Characteristics of Patients With COVID-19

The analyses included a total of 32 583 confirmed cases, among whom 15 766 (48.4%) were men and 16 817 (51.6%) were women (**Table**). The median age of the patients was 56.7 years (range, 0-103; interquartile range, 43.4-66.8), with the majority (n = 24 203, 74.3%) aged 40 to 79 years (Table).

The epidemic curve according to the symptom onset date and key interventions is shown in Figure 1. Most cases occurred between January 20 and February 6, with a spike on February 1. The epidemic curve with inclusion of clinically diagnosed cases is shown in eFigure 1 in the Supplement, and the epidemic curve limiting the sample to only severe and critical cases is shown in eFigure 2 in the Supplement; both showed similar patterns to the main analysis. There was a substantial delay between symptom onset date and laboratory confirmation date in the early periods, with the lag decreasing over time (median, 26, 15, 10, 6, and 3 days for the 5 periods, respectively; eFigure 3 in the Supplement).

Geographic Spread and Confirmed Case Rates

The outbreak started from the urban districts and gradually spread to the suburban and rural areas across the 5 periods. There were strong geographic differences in rates of confirmed cases, with the highest rates in the urban districts (**Figure 2**).

The daily confirmed case rate per million people increased from 2.0 (95% CI, 1.8-2.1) before January 10, to 45.9 (95% CI, 44.6-47.1) between January 10 and 22, and to 162.6 (95% CI, 159.9-165.3) between January 23 and February 1, and then decreased to 77.9 (95% CI, 76.3-79.4) between February 2 and 16, and 17.2 (95% CI, 16.6-17.8) after February 16 (**Figure 3**A; eTable 1 in the Supplement). Similar patterns were observed for men and women, with a slightly higher rate in women (43.7 [95% CI, 43.0-44.4]) compared with men (39.4 [95% CI, 38.8-40.0]) over the whole period (Figure 3A).

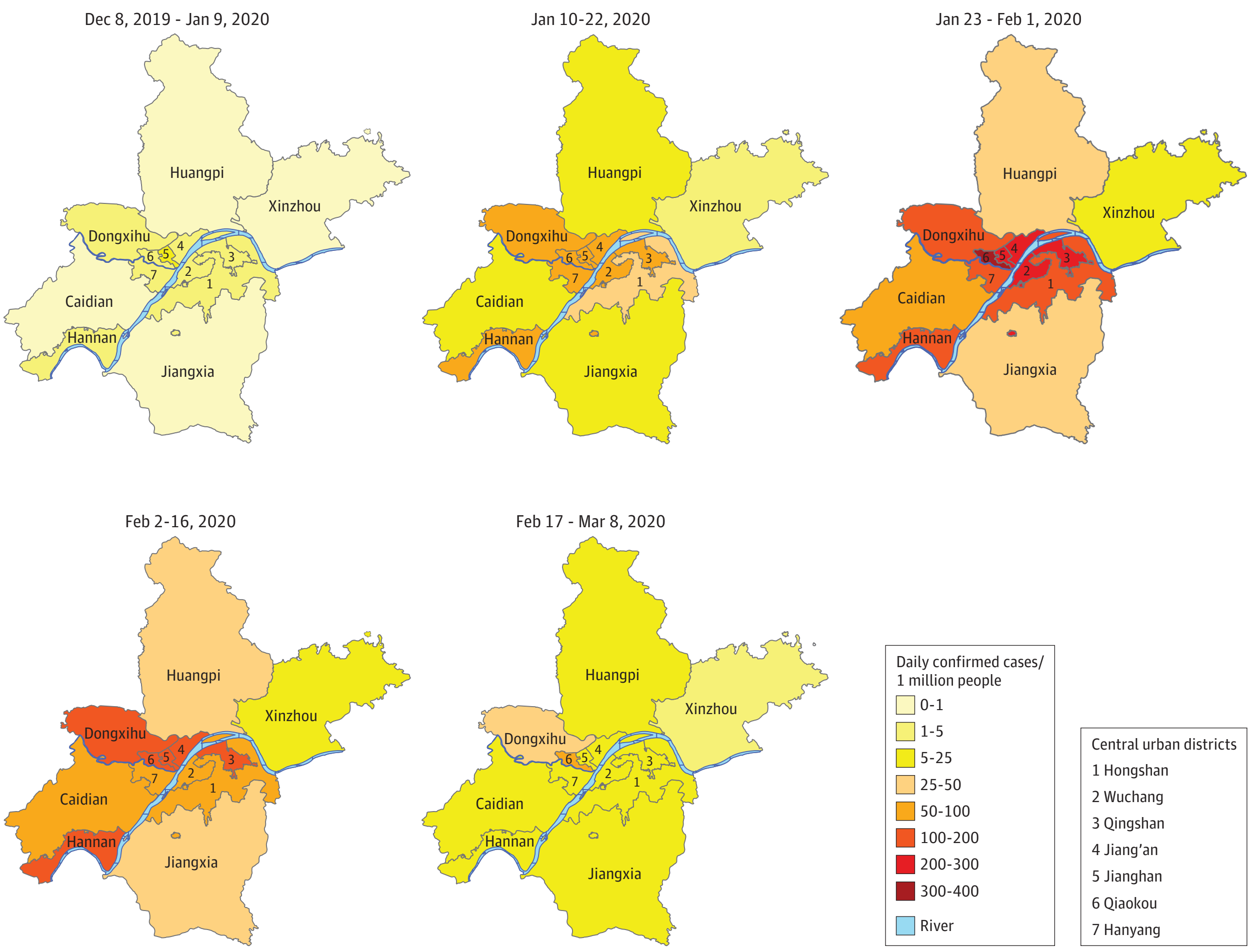
Table. Characteristics of Patients With Laboratory-Confirmed COVID-19 Across the 5 Periods in Wuhan, China[a]

	No. (%)					
Characteristics	**Dec 8, 2019-Jan 9, 2020**	**Jan 10-22, 2020**	**Jan 23-Feb 1, 2020**	**Feb 2-16, 2020**	**Feb 17-Mar 8, 2020**	**Total**
Total	550	5091	13 880	9972	3090	32 583
Sex						
Male	290 (52.7)	2503 (49.2)	6815 (49.1)	4822 (48.4)	1336 (43.2)	15 766 (48.4)
Female	260 (47.3)	2588 (50.8)	7065 (50.9)	5150 (51.6)	1754 (56.8)	16 817 (51.6)
Age, median (IQR), y	61.0 (50.4-69.2)	57.0 (45.1-66.5)	57.2 (44.9-66.9)	56.2 (42.6-66.6)	52.1 (36.2-66.5)	56.7 (43.4-66.8)
Age group, y						
0-19	1 (0.2)	17 (0.3)	83 (0.6)	212 (2.1)	223 (7.2)	536 (1.6)
20-39	61 (11.1)	913 (17.9)	2379 (17.1)	1881 (18.9)	726 (23.5)	5960 (18.3)
40-59	203 (36.9)	1937 (38.0)	5322 (38.3)	3759 (37.7)	1048 (33.9)	12 269 (37.7)
60-79	251 (45.6)	1987 (39.0)	5437 (39.2)	3514 (35.2)	745 (24.1)	11 934 (36.6)
≥80	34 (6.2)	237 (4.7)	659 (4.7)	606 (6.1)	348 (11.3)	1884 (5.8)
Health care workers	21 (3.8)	441 (8.7)	679 (5.5)	298 (3.0)	57 (1.8)	1496 (4.6)

Abbreviations: COVID-19, coronavirus disease 2019; IQR, interquartile range.

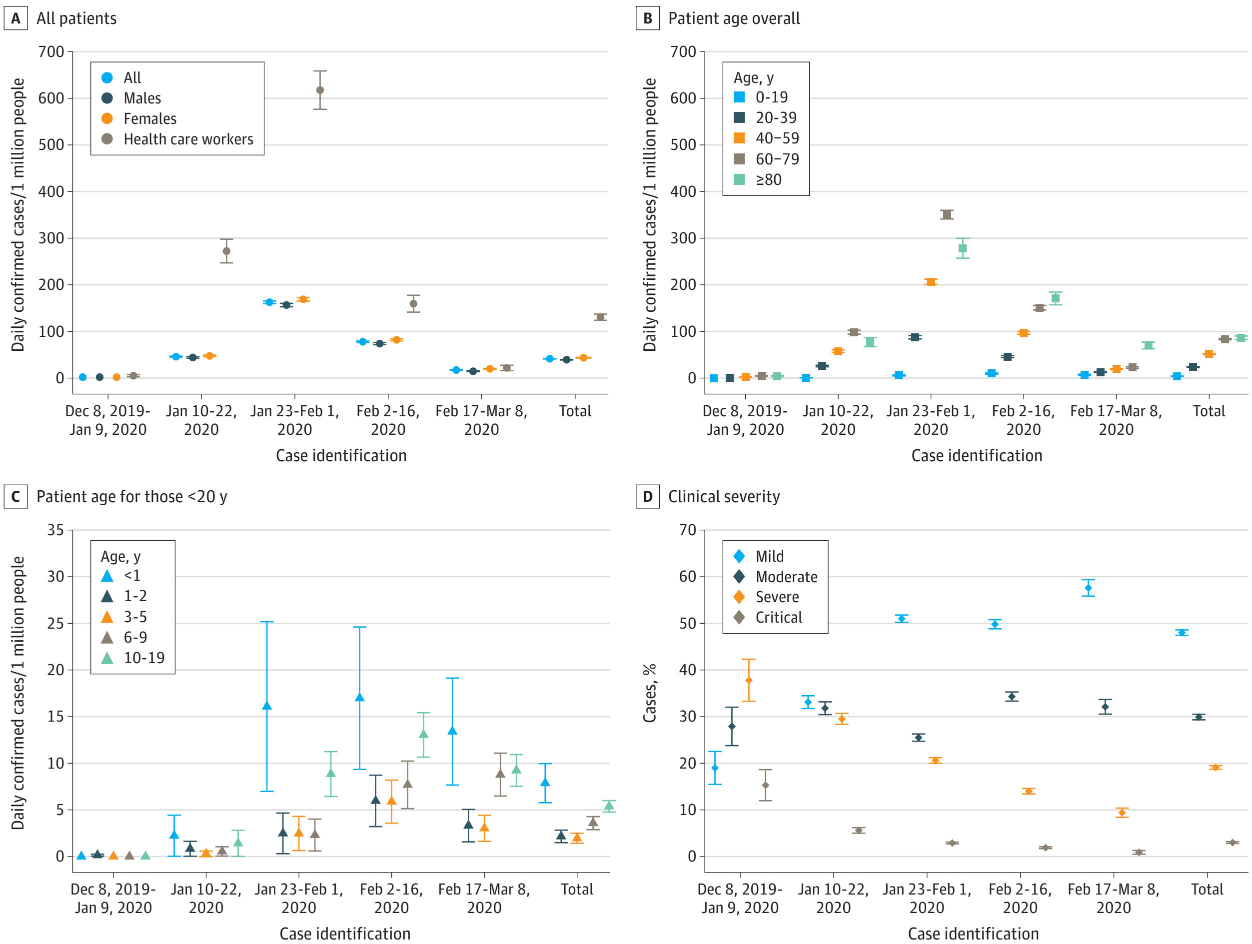
[a] The 5 periods were classified according to dates of key events and interventions from December 8, 2019, to March 8, 2020. Details are shown in Figure 1 and eMethods in the Supplement.

Figure 2. The Geographic Distribution of Daily Rates of COVID-19 Cases Across the 5 Periods in Wuhan, China



The daily rate of cases is expressed as number of laboratory-confirmed cases per day per million people, grouped by each of the 13 districts of the city of Wuhan. COVID-19 indicates coronavirus disease 2019.

Figure 3. Daily Rates of Cases in Different Groups and Proportion of Severity Categories Across the 5 Periods in Wuhan, China



The exact values for the daily rates of cases in panels A-C in different groups across the 5 periods are shown in eTable 2 in the Supplement. The clinical severity in panel D was defined according to the 7 editions of the Interim Diagnosis and Treatment of 2019 Novel Coronavirus Pneumonia,[14] and details are shown in the eMethods in the Supplement. Error bars indicate 95% CIs.

A total of 1496 local health care workers had confirmed cases, representing 4.6% of all cases (Table). The daily rate of cases in local health care workers (130.5 per million people [95% CI, 123.9-137.2]) was higher than that in the general population (41.5 per million people [95% CI, 41.0-41.9]) over the whole period. The rate among health care workers peaked in the third period (617.4 per million people [95% CI, 576.3-658.4]), but decreased in the last 2 periods when comprehensive personal protective equipment was more widely used (Figure 3A; eTable 1 in the Supplement).

Rates of confirmed cases and trends also differed by age. It peaked in the third period and declined thereafter for those older than 20 years, while it continued to increase for children and adolescents (age <20 years) (Figure 3B; eTable 1 in the Supplement), particularly for infants younger than 1 year (Figure 3C). The rate over the whole period among infants younger than 1 year was 7.9 per million people (95% CI, 5.8-10.0), while it ranged from 2.0 to 5.4 among other age groups of children and adolescents (Figure 3C; eTable 1 in the Supplement).

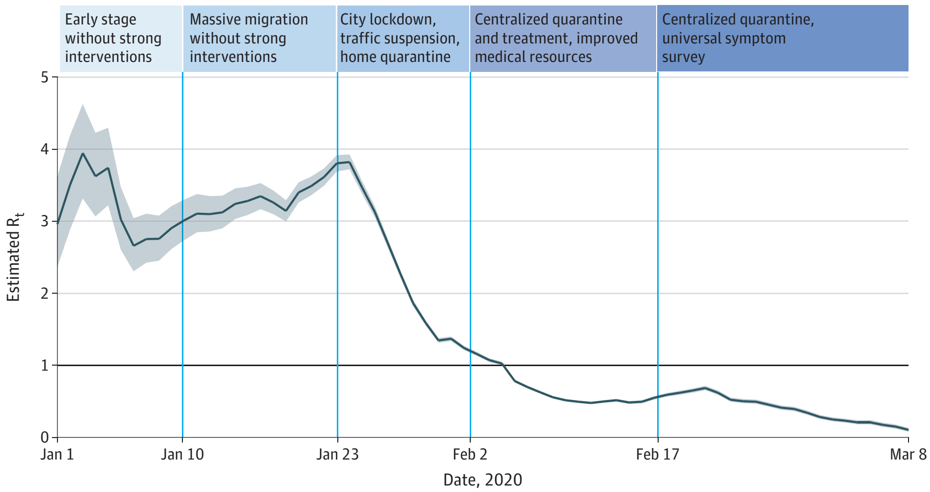
Clinical Severity of Disease

Confirmed cases with available data (n = 32 325) were classified into mild (n = 15 531, 48.0%), moderate (n = 9655, 29.9%), severe (n = 6169, 19.1%), and critical (n = 970, 3.0%) (Figure 3D). The proportion of severe and critical cases decreased gradually over time, accounting for 53.1%, 35.1%, 23.5%, 15.9%, and 10.3% of the classifiable cases in the 5 periods, respectively (Figure 3D).

The unadjusted proportion of severe and critical cases increased with age (4.10% in those aged <20 years, 12.1% in those aged 20-39 years, 17.4% in those aged 40-59 years, 29.6% in those aged 60-79 years, and 41.3% in those aged ≥80 years), and the corresponding multivariable-adjusted RRs (95% CIs) were 0.47 (0.31-0.70), 1.00 (reference), 1.41 (1.30-1.53), 2.33 (2.16-2.52), and 3.61 (3.31-3.95), respectively (eTable 2 in the Supplement).

Females were at lower risk of severe and critical disease than were males (unadjusted proportion, 20.6% vs 23.7%; adjusted RR, 0.90 [95% CI, 0.86-0.93]), while there were no significant differences in clinical severity between health care

Figure 4. The Effective Reproduction Number (R_t) Estimates Based on Laboratory-Confirmed Coronavirus Disease 2019 (COVID-19) Cases in Wuhan, China



The effective reproduction number R_t is defined as the mean number of secondary cases generated by a typical primary case at time *t* in a population, calculated for the whole period over a 5-day moving average. Results are shown since January 1, 2020, given the limited number of diagnosed cases and limited diagnosis capacity in December 2019. The darkened horizontal line indicates R_t = 1, below which sustained transmission is unlikely so long as antitransmission measures are sustained, indicating that the outbreak is under control. The 95% credible intervals (CrIs) are presented as gray shading. Daily estimates of R_t with 95% CrIs are shown in eTable 3 in the Supplement.

workers and other occupation groups (unadjusted proportion, 17.4% vs 22.3%; adjusted RR, 1.08 [95% CI, 0.96-1.21]).

Estimates of R_t

Estimates of the effective reproduction number R_t varied in the first period (**Figure 4**), gradually increased in the second period with a peak of 3.82 on January 24, and declined thereafter. The R_t fell below 1.0 on February 6, 2020, and further decreased to below 0.3 on March 1, 2020. The daily estimated values of R_t are shown in eTable 3 in the Supplement.

Discussion

In this cohort study, the number of incident COVID-19 cases, rates of confirmed cases, and R_t were reduced and the outbreak was under improved control in Wuhan after implementation of multifaceted public health measures (including but not limited to intensive intracity and intercity traffic restriction, social distancing measures, home confinement and centralized quarantine, and improvement of medical resources).

Among the 32 583 confirmed COVID-19 cases, females had a higher rate of confirmed cases compared with males, but males were more likely to have severe or critical illness. This is consistent with previous reports from China suggesting a higher crude fatality rate among men compared with women (2.8% vs 1.7%),[18,19] and another study in critically ill patients demonstrating that more men were affected (67%) than women (33%).[20] Although the reasons for these differences are unknown, it is possible that men were more likely to be current smokers[21] and had a higher proportion of comorbid conditions, which might worsen their prognosis. Also consistent with early reports, younger people were less likely to be affected,[8,18,22] although the rate continued to increase in children and adolescents over time. Infants younger than 1 year had the highest rate of cases among children and adolescents. These results suggest that vigorous efforts should be made to protect and reduce transmission and symptom progression in vulnerable populations including both elderly people and young children.[22,23]

The rate of cases in health care workers was substantially higher than in the general population between January 11 and February 1, indicating a high risk of nosocomial infection. This might be due to lower awareness and inadequate use of personal protective equipment in the early periods in this study, and later a severe shortage of medical resources. The rate of confirmed cases among local health care workers quickly decreased in the later periods, after increasing awareness of and wider use of personal protective equipment, proper training, adequate hospital-level prevention and management, and support from more than 30 000 health care workers from other provinces of China. Furthermore, none of the health care workers from other provinces were infected, supporting the importance of carefully protecting health care workers in the outbreak of a high transmissible infectious disease.[24]

The findings of this study may be valuable in the current efforts to combat the global pandemic of COVID-19. Many countries, regions, and communities have or will confront a surge in incident cases,[1] similar to what happened in Wuhan in January. In Wuhan, vigorous and multifaceted measures of containment, mitigation, and suppression were temporally associated with improved control of the epidemic when there was neither effective drug nor vaccine. In a city with 10 million residents, mitigation measures, such as traffic restriction, cancellation of social gatherings, and home quarantine, were associated with a reduction in the degree of transmission. However, despite these interventions, the confirmed case rate continued to increase in the third period, perhaps in part due to shortages of pharmaceuticals and medical equipment and delayed diagnosis and access to medical treatment. Without rapid diagnosis, the risk of cross-infection in hospitals was high and patients likely continued to infect family members and close contacts. It has been reported that about 80% of the cluster transmission occurred in families in China.[22]

With the improvement of medical resources (designated hospitals and wards, use of personal protective equipment, increased testing capacity and accelerated reporting, and timely medical treatment) and increasing supply of health care workers, the Chinese government issued a centralized quarantine and treatment policy on February 2. All confirmed and presumptive cases, those with fever or respiratory symptoms, as well as close contacts of confirmed cases were allocated to designated hospitals or facilities. Centralized quarantine of patients and close contacts appears to have been associated with a reduction in in-hospital, household, and community transmission. Between February 16 and 18, the government further initiated a door-to-door and individual-to-individual universal symptom survey to single out presumptive cases in the community, which was associated with further reductions in the spread of COVID-19 in Wuhan.

Previous studies have reported varied R_O (range 1.40-6.49 with a mean of 3.28) for the COVID-19 outbreak due to different data sources, time periods, and statistical methods.[25] Using the first 425 patients in Wuhan, an early study reported an R_O of 2.20 based on the growth rate of the epidemic curve and the serial interval,[8] while a recent analysis based on a transmission network model reported an R_O of 3.58,[26] similar to the current estimates in the first and second period. This study found that the implementation of public health interventions was associated with a reduction in R_t to below 1.0 on February 6 and to below 0.3 on March 1, which may have implications for global efforts to contain the pandemic more broadly.[27]

Limitations

The study has several limitations. First, the Chinese government implemented multiple interventions at the same time or in a short timeframe to control the outbreak, and thus individual strategies could not be evaluated. In addition, the observational study design precludes causal inference. However, clinical trials were not feasible or ethical under such public health emergencies, and there are not yet data available to compare the experience in Wuhan with other outbreak areas pursuing different policies.

Second, data were extracted from the infectious disease reporting system, and no information was available for other epidemiological variables and clinical characteristics, such as incubation period, time to hospitalization, time to discharge, medical treatment strategies, and vital status. Cases occurring in the early days of a new period included infections that were acquired during the previous period, and thus there were lags for the interventions to take effect.

Third, there were unexplained peaks in the epidemic curve, particularly a surge on February 1. Fourth, no data were available on the diagnostic testing pattern, ascertainment rate, and proportion of asymptomatic cases. The shortage of testing in the early periods suggests that ascertainment bias may in part explain the initially high proportion of severe and critical cases; testing was widely available in the fourth and fifth periods and these estimates may reflect a more accurate measure of disease severity. There were likely substantial proportions of undetected cases in Wuhan in early periods,[9-11] and asymptomatic cases could be infectious to others.[28-30] Further field investigations and serologic studies are needed to confirm the ascertainment rate and the effect of unascertained cases (asymptomatic cases or patients with mild symptoms who could recover without seeking medical care) on the epidemic course[31,32]; this represents an important area for future study.

Conclusions

A series of multifaceted public health interventions was temporally associated with improved control of the COVID-19 outbreak in Wuhan, China. These findings may inform public health policy in other countries and regions to combat the global pandemic of COVID-19.

ARTICLE INFORMATION

Accepted for Publication: April 3, 2020.

Published Online: April 10, 2020. doi:10.1001/jama.2020.6130

Author Affiliations: Department of Epidemiology and Biostatistics, School of Public Health, Tongji Medical College, Huazhong University of Science and Technology, Wuhan, China (Pan, Liu, C. Wang, Hao, Q. Wang, Huang, Wei); Department of Occupational and Environmental Health, Ministry of Education Key Laboratory of Environment and Health, and State Key Laboratory of Environmental Health (Incubating), School of Public Health, Tongji Medical College, Huazhong University of Science and Technology, Wuhan, China (Guo, Wu); School of Public Health, Ministry of Education Key Laboratory of Public Health Safety, Fudan University, Shanghai, China (He, Yu); Department of Biostatistics, Harvard T.H. Chan School of Public Health, Boston, Massachusetts (Lin); Department of Statistics, Harvard University, Boston, Massachusetts (Lin).

Author Contributions: Drs Wei and Wu had full access to all of the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis. Joint first authors are Drs Pan, Liu, C. Wang, Guo, and Hao.
Concept and design: Pan, C. Wang, Wu.
Acquisition, analysis, or interpretation of data: All authors.
Drafting of the manuscript: Pan, C. Wang, Lin.
Critical revision of the manuscript for important intellectual content: Liu, Guo, Hao, Q. Wang, Huang, He, Yu, Lin, Wei, Wu.
Statistical analysis: Pan, Liu, C. Wang, Guo, Hao, Q. Wang, Huang, Lin, Wei.
Obtained funding: Wu.
Administrative, technical, or material support: He, Yu, Wu.
Supervision: C. Wang, Lin, Wu.

Conflict of Interest Disclosures: Dr Yu reported receiving grants from the National Natural Science Foundation of China, the Program of Shanghai Academic/Technology Research Leader, and the National Science and Technology Major Project of China during the conduct of the study; grants from Sanofi Pasteur, GlaxoSmithKline, Yichang HEC Changjiang Pharmaceutical Company, and bioMérieux Diagnostic Product (Shanghai) outside the submitted work. No other disclosures were reported.

Funding/Support: This study was partly supported by the Fundamental Research Funds for the Central Universities (2019kfyXMBZ015), the 111 Project (Drs Pan, Liu, C. Wang, Guo, Hao, Q. Wang, Huang, Wei, and Wu). Dr Lin is supported by Harvard University.

Role of the Funder/Sponsor: The funders had no role in the design and conduct of the study; collection, management, analysis, and interpretation of the data; preparation, review, or approval of the manuscript; and decision to submit the manuscript for publication.

Additional Contributions: We are grateful to all staff at the national, provincial, and municipal Center for Disease Control and Prevention for providing the data and all medical staff members and field workers who are working on the frontline of caring for patients and collecting the data.

REFERENCES

1. World Health Organization. Coronavirus disease 2019 (COVID-19) situation report-76. Accessed April 6, 2020. https://www.who.int/docs/default-source/coronaviruse/situation-reports/20200405-sitrep-76-covid-19.pdf?sfvrsn=6ecf0977_2

2. Guan WJ, Ni ZY, Hu Y, et al; China Medical Treatment Expert Group for Covid-19. Clinical characteristics of coronavirus disease 2019 in China. *N Engl J Med*. Published online February 28, 2020. doi:10.1056/NEJMoa2002032

3. Wang D, Hu B, Hu C, et al. Clinical characteristics of 138 hospitalized patients with 2019 novel coronavirus-infected pneumonia in Wuhan, China. *JAMA*. 2020;323(11):1061-1069. doi:10.1001/jama.2020.1585

4. Chen N, Zhou M, Dong X, et al. Epidemiological and clinical characteristics of 99 cases of 2019 novel coronavirus pneumonia in Wuhan, China: a descriptive study. *Lancet*. 2020;395(10223):507-513. doi:10.1016/S0140-6736(20)30211-7

5. Huang C, Wang Y, Li X, et al. Clinical features of patients infected with 2019 novel coronavirus in Wuhan, China. *Lancet*. 2020;395(10223):497-506. doi:10.1016/S0140-6736(20)30183-5

6. Chang D, Lin M, Wei L, et al. Epidemiologic and clinical characteristics of novel coronavirus infections involving 13 patients outside Wuhan, China. *JAMA*. 2020;323(11):1092-1093. doi:10.1001/jama.2020.1623

7. Xu XW, Wu XX, Jiang XG, et al. Clinical findings in a group of patients infected with the 2019 novel coronavirus (SARS-Cov-2) outside of Wuhan, China: retrospective case series. *BMJ*. 2020;368:m606. doi:10.1136/bmj.m606

8. Li Q, Guan X, Wu P, et al. Early transmission dynamics in Wuhan, China, of novel coronavirus-infected pneumonia. *N Engl J Med*. 2020;382(13):1199-1207. doi:10.1056/NEJMoa2001316

9. Wu JT, Leung K, Leung GM. Nowcasting and forecasting the potential domestic and international spread of the 2019-nCoV outbreak originating in Wuhan, China: a modelling study. *Lancet*. 2020;395(10225):689-697. doi:10.1016/S0140-6736(20)30260-9

10. Kucharski AJ, Russell TW, Diamond C, et al; Centre for Mathematical Modelling of Infectious Diseases COVID-19 working group. Early dynamics of transmission and control of COVID-19: a mathematical modelling study. *Lancet Infect Dis*. Published online March 11, 2020. doi:10.1016/S1473-3099(20)30144-4

11. Li R, Pei S, Chen B, et al. Substantial undocumented infection facilitates the rapid dissemination of novel coronavirus (SARS-CoV2). *Science*. Published online March 16, 2020. doi:10.1126/science.abb3221

12. Chinazzi M, Davis JT, Ajelli M, et al. The effect of travel restrictions on the spread of the 2019 novel coronavirus (COVID-19) outbreak. *Science*. 2020; eaba9757. Published online March 6, 2020. doi:10.1126/science.aba9757

13. Tian H, Liu Y, Li Y, et al. An investigation of transmission control measures during the first 50 days of the COVID-19 epidemic in China. *Science*. Published online March 31, 2020. doi:10.1126/science.abb6105

14. National Health Commission of the People's Republic of China. Interim diagnosis and treatment of 2019 novel coronavirus pneumonia. 7th ed. March 3, 2020. Accessed March 4, 2020. http://www.nhc.gov.cn/yzygj/s7653p/202003/46c9294a7dfe4cef80dc7f5912eb1989.shtml

15. Phelan AL, Katz R, Gostin LO. The novel coronavirus originating in Wuhan, China: challenges for global health governance. *JAMA*. 2020;323(8):709-710. doi:10.1001/jama.2020.1097

16. Spiegelman D, Hertzmark E. Easy SAS calculations for risk or prevalence ratios and differences. *Am J Epidemiol*. 2005;162(3):199-200. doi:10.1093/aje/kwi188

17. Cori A, Ferguson NM, Fraser C, Cauchemez S. A new framework and software to estimate time-varying reproduction numbers during epidemics. *Am J Epidemiol*. 2013;178(9):1505-1512. doi:10.1093/aje/kwt133

18. The Novel Coronavirus Pneumonia Emergency Response Epidemiology Team. Vital surveillances: the epidemiological characteristics of an outbreak of 2019 novel coronavirus diseases (COVID-19)—China, 2020. *China CDC Weekly*. 2020;2:113-122.

19. Wu Z, McGoogan JM. Characteristics of and important lessons from the coronavirus disease 2019 (COVID-19) outbreak in China: summary of a report of 72 314 cases from the Chinese Center for Disease Control and Prevention. *JAMA*. 2020;323(13):1239-1242. doi:10.1001/jama.2020.2648

20. Yang X, Yu Y, Xu J, et al. Clinical course and outcomes of critically ill patients with SARS-CoV-2 pneumonia in Wuhan, China: a single-centered, retrospective, observational study. *Lancet Respir Med*. S2213-2600(20)30079-5. Published online February 24, 2020. doi:10.1016/S2213-2600(20)30079-5

21. Vardavas CI, Nikitara K. COVID-19 and smoking: a systematic review of the evidence. *Tob Induc Dis*. 2020;18:20. doi:10.18332/tid/119324

22. Report of the WHO-China Joint Mission on Coronavirus Disease 2019 (COVID-19). Accessed March 2, 2020. https://www.who.int/docs/default-source/coronaviruse/who-china-joint-mission-on-covid-19-final-report.pdf

23. Wang G, Zhang Y, Zhao J, Zhang J, Jiang F. Mitigate the effects of home confinement on children during the COVID-19 outbreak. *Lancet*. 2020;395(10228):945-947. doi:10.1016/S0140-6736(20)30547-X

24. Adams JG, Walls RM. Supporting the health care workforce during the COVID-19 global epidemic. *JAMA*. Published online March 12, 2020. doi:10.1001/jama.2020.3972

25. Liu Y, Gayle AA, Wilder-Smith A, Rocklöv J. The reproductive number of COVID-19 is higher compared to SARS coronavirus. *J Travel Med*. 2020;27(2):taaa021. doi:10.1093/jtm/taaa021

26. Chen TM, Rui J, Wang QP, Zhao ZY, Cui JA, Yin L. A mathematical model for simulating the phase-based transmissibility of a novel coronavirus. *Infect Dis Poverty*. 2020;9(1):24. doi:10.1186/s40249-020-00640-3

27. Fong MW, Gao H, Wong JY, et al. Nonpharmaceutical measures for pandemic influenza in nonhealthcare settings-social distancing measures. *Emerg Infect Dis*. 2020;26(5). Published online February 6, 2020. doi:10.3201/eid2605.190995

28. Bai Y, Yao L, Wei T, et al. Presumed asymptomatic carrier transmission of COVID-19. *JAMA*. Published online February 21, 2020. doi:10.1001/jama.2020.2565

29. Kam KQ, Yung CF, Cui L, et al. A well infant with coronavirus disease 2019 (COVID-19) with high viral load. *Clin Infect Dis*. 2020;ciaa201. Published online February 28, 2020. doi:10.1093/cid/ciaa201

30. Tong ZD, Tang A, Li KF, et al. Potential presymptomatic transmission of SARS-CoV-2, Zhejiang Province, China, 2020. *Emerg Infect Dis*. 2020;26(5). Published online February 6, 2020. doi:10.3201/eid2605.200198

31. Lipsitch M, Swerdlow DL, Finelli L. Defining the epidemiology of Covid-19: studies needed. *N Engl J Med*. 2020;382(13):1194-1196. doi:10.1056/NEJMp2002125

32. Morens DM, Daszak P, Taubenberger JK. Escaping pandora's box—another novel coronavirus. *N Engl J Med*. 2020;382(14):1293-1295. doi:10.1056/NEJMp2002106