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Do Stay at Home Orders and Cloth Face Coverings Control COVID-19 in New York City? Results From a SIER Model Based on Real-world Data

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Background. Public health interventions have been implemented to contain the outbreak of coronavirus disease 2019 (COVID-19) in New York City. However, the assessment of those interventions—for example, social distancing and cloth face coverings—based on real-world data from published studies is lacking.

Methods. The Susceptible-Exposed-Infectious-Removed (SEIR) compartmental model was used to evaluate the effect of social distancing and cloth face coverings on the daily culminative laboratory confirmed cases in New York City (NYC) and COVID-19 transmissibility. The latter was measured by R_t reproduction numbers in 3 phases that were based on 2 interventions implemented during this timeline.

Results. Transmissibility decreased from phase 1 to phase 3. The initial R_0 was 4.60 in phase 1 without any intervention. After social distancing, the R_t value was reduced by 68%, while after the mask recommendation, it was further reduced by ~60%.

Conclusions. Interventions resulted in significant reduction of confirmed case numbers relative to predicted values based on the SEIR model without intervention. Our findings highlight the effectiveness of social distancing and cloth face coverings in slowing down the spread of severe acute respiratory syndrome coronavirus 2 in NYC.

Keywords. cloth face coverings; COVID-19; New York City; pandemic; social distancing.

Novel coronavirus broke out in Wuhan, China, in December of 2019. It then spread rapidly across the nation and the world. New York City, an international metropolitan area with more than 8 million residents, was disproportionately affected by coronavirus disease 2019 (COVID-19) relative to other US cities and has the highest number of confirmed cases in United States. To control the outbreak, a series of interventions have been implemented by authorities at different levels. Among them, social distancing, closing nonessential services, and wearing masks are the most common measures. Social distancing was announced as a measure that all Americans should undertake by the federal government on March 16, 2020 [1]. It was the first time in US history, or in human history, that such social distancing measures were

applied at this scale. Furthermore, the Centers for Disease Control and Prevention (CDC) recommended on April 3 that all Americans wear cloth face coverings/masks in public places [2]. This new recommendation was different from the previous messaging that only those with confirmed COVID-19 and health care workers should wear a mask. Face cloths or mask coverings are thought to prevent the spread of the virus for asymptomatic carriers and presymptomatic cases in public settings. Asymptomatic carriers of COVID-19 have been reported to have the capacity to spread severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) [3]. However, cloth coverings or cloth masks only prevent transmission in one-third of symptomatic patients. Cloth face covering is an effective prevention method at the individual level for those susceptible to COVID-19. Of note, indirect contact also plays a key role in the transmission of COVID-19 [4], which might not be controlled by social distancing or cloth face covering.

The effects of wearing masks and cloth face covers on the spread of COVID-19 have not been fully understood at a populations level in the United States. Until now, most evaluations of mask effectiveness have been from evaluations of interventions in China. Some aggressive interventions, such as traffic restrictions or even complete city lockdowns such as in Wuhan city might not be suitable in the United States

due to differences in the acceptability of such restrictions socially and culturally between China and the United States. It is more likely that the synthesis of several intervention outcomes will prove the most effective stragegy; some of these interventions may not be viable in the United States. Initial CDC guidance did not include the recommendation of cloth face coverings, and when this recommendation came out, the general public was confused about the value of instituting this at an individual level. Additionally, cloth face coverings were not easily attainable for most people either.

Most trajectories and projections of COVID-19 spread have been based on the classic Susceptible-Exposed-Infectious-Removed (SEIR) model. Questions arise on how quickly these interventions can take effect and how many days these interventions delay the peak time and to what extent they reduce the peak and spread of SARS-CoV-2. To the best of our knowledge, no study has addressed the effectiveness of social distancing and cloth face coverings for controlling COVID-19 in New York City. Hence, this study aims to evaluate the effectiveness of these 2 interventions in New York City in preventing the spread of COVID-19.

METHODS

Data Source
In the current study, we used the official published daily data on COVID-19, including daily cumulated data on confirmed new and hospitalized COVID-19 cases and deaths. The epidemiological data in New York City (NYC) from March 1 (the date of the first confirmed cases in NYC) to April 10, 2020, were obtained from the official website of the NYC (https://www1. nyc.gov/) and utilized for analysis in this study.

Case Definitions
In this study, COVID-19 cases were defined as people who had a positive COVID-19 laboratory test, according to the Department of Health of NYC [5]. A COVID-19 death case was defined as being confirmed from the city's Office of the Chief Medical Examiner and Department of Health of NYC Bureau of Vital Statistics. Usually, the city's death case numbers are lower than the state's numbers due to the time required by the city to confirm and report a death. Only laboratory-confirmed positive cases were included in primary analyses for the consistency of case definition throughout the time periods examined in this study. There were an additional 17 365 cases of clinically diagnosed COVID-19 (ie, designated by symptom report and chest x-ray, but without a positive RT-PCR result) in the data set.

Interventions
March 1, 2020, was the date of the first confirmed case of COVID-19 in NYC. The NYC authority then launched their emergency epidemic prevention and control measures. There were at least 2 interventions implemented in different phases in NYC to control COVID-19.

Social Distancing
Social distancing refers to a set of nonpharmaceutical interventions or measures taken to prevent the spread of a contagious disease by maintaining a physical distance between people and reducing the number of times people come into close contact with each other. One important element is keeping a distance of at least 6 feet, or 2 meters, from others and avoiding gathering in large groups. Social distancing also includes avoiding physical contact, school closures, workplace closures, canceling mass gatherings, imposing travel restrictions, and other similar measures. NYC followed the federal government's social distancing guidelines and recommendations of March 16, 2020 [1].

Cloth Face Covering (Mask Recommendations)
Cloth face coverings have been recommended as a low-cost and voluntary public health measure. They can be fashioned from household items, such as bandanas and dish towels, or sewn at home from store-bought fabric [2]. On April 2, 2020, the NYC mayor announced that all New Yorkers should start wearing "face coverings" when traveling outside of the home [6]. On April 3, the CDC recommended that Americans consider wearing cloth face coverings in public, but acknowledged that this recommendation would remain voluntary.

SEIR Model
To evaluate the COVID-19 transmission control measures put in place in NYC, the SEIR compartmental model was used, which has been applied to many other respiratory diseases [7, 8]. In this model, individuals could be in 1 of 4 states: susceptible (S), exposed (E = being infected but not infectious), infected (I = being infectious), and recovered (R). The movements across states are illustrated by the following flowchart: solid lines with arrows, indicating the movement between 2 states and the corresponding direction, and the dashed gray line with an arrow, indicating that the level of infected affects the rate of movement from S to E. Note that E is also called the incubation or latent state (Figure 1).

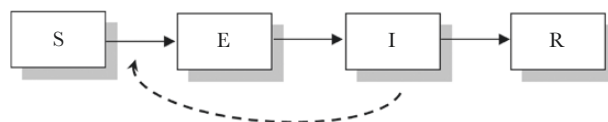The dynamic process of SEIR is characterized by the following equations:

Figure 1. Transmission model for the natural history of coronavirus disease 2019.

$$\frac{dS}{dt} = \mu - \beta IS - \mu S$$

$$\frac{dE}{dt} = \beta IS - (\sigma + \mu) E$$

$$\frac{dI}{dt} = \sigma E - (\gamma + \mu) I$$

$$\frac{dR}{dt} = \gamma I - \mu R$$

Parameter of the Model

In the above-mentioned SEIR model, β is the product of contact rates and transmission probability, γ is the recovery or removed rate, and μ is the natural birth/death rate. In addition, $T_E = 1/\sigma$ and $T_I = 1/\gamma$ represent the average incubation and infection periods, respectively, and $T_g = T_E + T_I$ is used to approximate the generation time; $S + E + I + R \leq 1S$ is typically assumed.

For the SEIR model, the basic reproduction number is R_0, and the expected number of new infections from a single infection can be computed as $R_0 = \frac{\beta \sigma}{(\sigma+\mu)(\gamma+\mu)}$ or alternatively, $R_0 = 1 + \lambda T_g + \rho (1 - \rho) \left(\lambda T_g\right)^2$, where $\rho = T_E / T_g$, and λ is the growth rate in the exponential growth period. To estimate R_0 based on observed data, various approaches have been used, including exponential growth rate [9] and maximum likelihood method [10]. Simulation-confirmed numbers using R_0 based on varied attack rates have also been applied [11].

In our analysis, the initial R_0 was estimated using the R_0 package in R (www.r-project.org) [12], which has various methods including those mentioned above. For simplicity, we assume that the national birth/death rate is low enough to be 0 in the pandemic in NYC (that is, $\mu \approx 0$). The effect of disease control may be captured by the proportional reduction in β and the effective R_0 at different stages of the outbreak, particularly for the epidemic dynamics for different situations. When $R_0 > 1$, the disease can spread, while at $R_0 < 1$ the spreading stops.

As for the latent and infectious period, the range was set at 3–6 days, which is consistent with previous studies; for example, the latent and infectious periods are approximately 3.69 and 3.48 days in a study from China [13], while another Chinese national study using data from outside Wuhan indicated that the mean incubation period for the entire period (range) was estimated at 5.2 (1.8–12.4) days and the mean serial interval was 5.1 days [14].

From the epidemiological viewpoint, social distancing is a relatively mild intervention to reduce people's contact in order to decrease potential transmission of SARS-CoV-2, while wearing a mask or using a cloth face covering addresses the attack rate more aggressively, which eventually decreases the same component in the epidemiological dynamical model.

Of note, wearing a mask might be more accepted by the general public than generally thought. The implementation of face masks can be done at the individual level. Thus, it might result in high compliance compared with social distancing because it does not rely on the behavior and cooperation of other people.

R_0 was estimated using the R_0 package [12] in R (www.r-project.org), which has various methods including the 2 mentioned above. Other statistical analyses were performed using SAS statistical software, version 9.4 (SAS Institute Inc). P values were 2-tailed, with statistical significance set at .05.

Pandemic Timeline

The time period of the pandemic in NYC could be categorized into 3 phases according to the intervention implementation on a timeline. Phase 1 (no intervention) was from the first confirmed case of COVID-19 in NYC to when social distancing was implemented in NYC on March 16, 2020. During this period, no intervention was implemented on a large scale to prevent the spread of SARS-CoV-2. Thus, there was natural spread of COVID-19 within the susceptible population. The second phase was from March 16 to April 3, when NYC announced the implementation of a social distancing policy in an effort to reduce the attack rate of SARS-CoV-2. In addition to social distancing, other measures included canceling public events and shutting down public schools. The third phase, from April 6 on, was when the CDC changed the recommendation regarding mask wearing for the general public and announced the recommendation for cloth face coverings in public settings. Figure 2 shows the intervention implementation phases illustrated on a timeline.

Sensitivity Analysis

A sensitivity analysis was conducted to test the stability of the modeling given the difference in the initial R_0 in the different percentages based on reduced attack rate. Four scenarios for R_0 reduction due to cloth face covering (mask recommendations) were considered, including 30%, 40%, 50%, and 60%.

RESULTS

Current Situation

In the current study, there was 122 148 confirmed cases in NYC through April 17. Among them, 32 823 (27%) people were hospitalized, and 7890 (6.45%) died. There was age and gender variation for COVID-19 infection and death rates ($P < .05$). People 75 years old and older had significantly higher infection rates, hospitalization rates, and death rates compared with those in younger age groups ($P < .05$). Also, males had higher rates of infection than females ($P < .05$). There was geo-spatial variation in the boroughs for infections rates as well ($P < .05$), with Staten Island having the highest positive case rates.
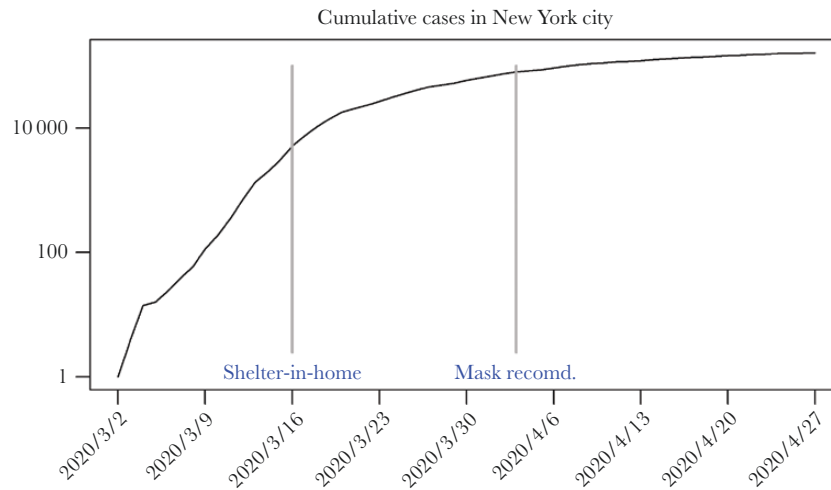
Figure 2. Semilogarithmic scale of cumulative laboratory-confirmed coronavirus disease 2019 cases in NYC on a timeline.

Trend of the Epidemic

By March 16, 2020, there were 464 confirmed cases, with 10 (2.2%) deaths in NYC. On April 3, there were 56 289 confirmed cases, with 1869 (3.3%) deaths. The details of the different time points are shown in Table 1. The linear trends (semi-log) of the daily cumulative cases of the COVID-19 pandemic in NYC are shown in Figure 2. From phases 1 to 3, the slopes of cumulative cases declined, indicating that the increase in infection rate significantly declined ($P < .05$), although the cumulative cases increased.

In phase 3, the cumulative confirmed COVID-19 cases after implementation of social distancing plus mask recommendation (cloth face covering) fell in the interval of the predication, a reduction of R_t 50%–60% (Figure 3). In addition, the accumulation of confirmed and estimated COVID-19 cases from simulations with and without interventions implemented in New York City for the 3 phases in log scale was shown in Figure 4.

Effective Reproduction Number

The effective reproduction number (R_t) reflects the transmission capacity, and it can also be used to evaluate the effectiveness of the interventions. Several different methods were used to calculate the R_t, including exponential growth and maximum likelihood. R_t varied during the different phases (Figure 5). The

initial R_0 was 4.60 in phase 1 without any intervention. It decreased to 1.47 in phase 2 from March 17 to April 3 and continued to decline to 0.59. After social distancing, the R_t value was reduced by 68%, while after the mask recommendation, it is further reduced to about 59.8%.

Projection With and Without Interventions

The trajectory of the different combinations of the interventions at different time points was estimated (Table 1). According to the modeling, if no intervention was implemented, there would be 4 680 000 confirmed COVID-19 cases by April 3. Fortunately, there were only 56 289 confirmed cases (1.21% of the projection) by April 3 in NYC after implementation of social distancing. Similarly, if only social distancing had been implemented (without cloth face coverings) starting March 16, the projected number would have been 287 000 by April 17. However, the current number from the existing data, as of April 3, is 122 148 (only 42.6% of 287 000) after implementation of both social distancing and cloth face covering. Given implementation of both social distancing and cloth face covering on March 16, the trajectory of the confirmed cases through May 1 would range from 139 900 to 294 500, whereas the trajectory of predicted numbers would be 8 320 000 without intervention and 911 000 with only social distancing implemented.

DISCUSSION

The value of R_0 of COVID-19 in NYC was 4.80, which indicates that COVID-19 is very contagious. This value is higher than influenza, for which the R_0 is around 2.0. It is higher than the estimated value of 2.2 from Wuhan [15] and 2.6 from Wenzhou [16]. However, our value was consistent with the R_0 value of 5.7 (95% CI, 3.8–8.9) from Wuhan in the early stage of the outbreak based on a collected and expanded set of case reports across China from publicly available information [17]. Also,

Table 1.   The Number of COVID-19 Cases by Simulation With and Without Interventions

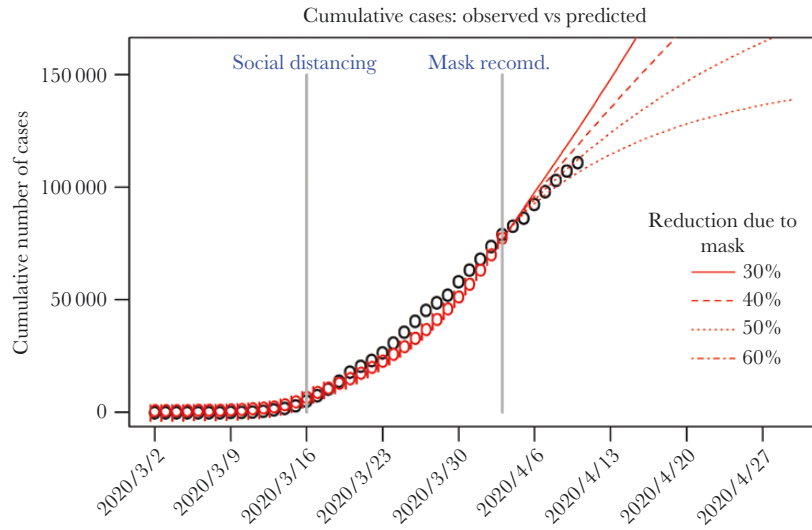|	No Intervention	Social Distancing	Social Distancing & Cloth Face Covering
Mar 16	464	NA	NA
Apr 3	~4.68*10^6	56 289	NA
Apr 17	~8.27*10^6	~287 000	122 148
May 1	~8.32*10^6	~911 000	~139 900–294 500

Cumulative cases: observed vs predicted

Figure 3. Comparison of cumulative confirmed coronavirus disease 2019 (COVID-19) cases with and without implementation of interventions in New York City for the 3 phases (o = observation and p = prediction). Prediction was made using the SEIR model without intervention for data between March 1 and March 16; prediction was based on the SEIR model with social distancing between March 16 and April 3, and the SEIR model with both social distancing and cloth face covering was used for prediction after April 3. Red lines represent the projection of simulation with social distancing from March 16 and implementation of the recommendation for social distance and cloth face covering, assuming various levels of effectives of the policies.

our estimation of R_0 fell within the estimated range (1.83–5.99) from another study, which used data from in and outside of China [18]. The differences in R_0 values could be partially due to the different methodologies used in these studies [19].

Our results are in line with another study in Jena, Germany, which indicated that the introduction of face masks beginning in April greatly reduced the cases of new infections over the next 20 days by almost 25% relative to the synthetic control group [20]. This study found that face masks may have made

a difference in the spread of COVID-19, particularly in larger cities with higher population densitye and accordingly higher intensity of social interaction.

Social distancing and cloth face covering (ie, a mask) are 2 of the most common measures recommended by authorities to control COVID-19. The effective reproduction number (R_t) characterizes the transmissibility of contagious diseases. Once R_t is less than 1, the number of new cases is declining and the disease will stop spreading ($R_t = R_0 X$, where X refers to the fraction
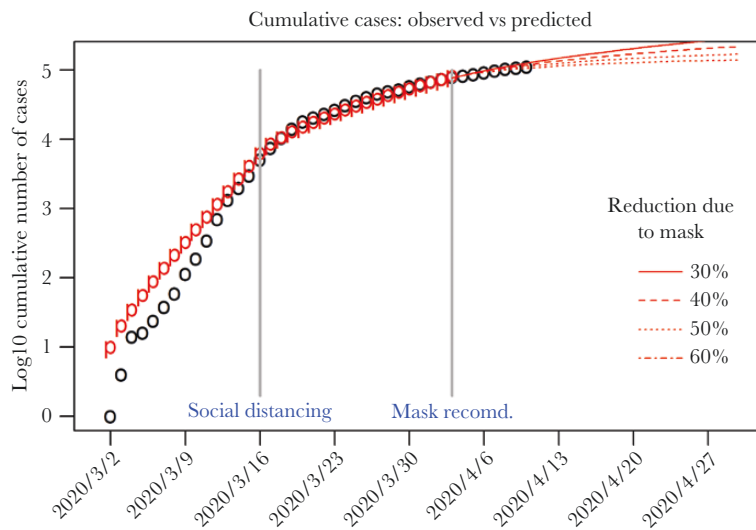
Cumulative cases: observed vs predicted

Figure 4. Sensitivity analyses for the different combined parameters (Simal log scale). "o" and "p" represent cumulative case numbers that were observed from the real world and that were predicted, respectively. Red lines represent the projection of simulation with social distancing from March 16 and implementation of the recommendation for social distance and cloth face covering, assuming various levels of effectives of the policies.
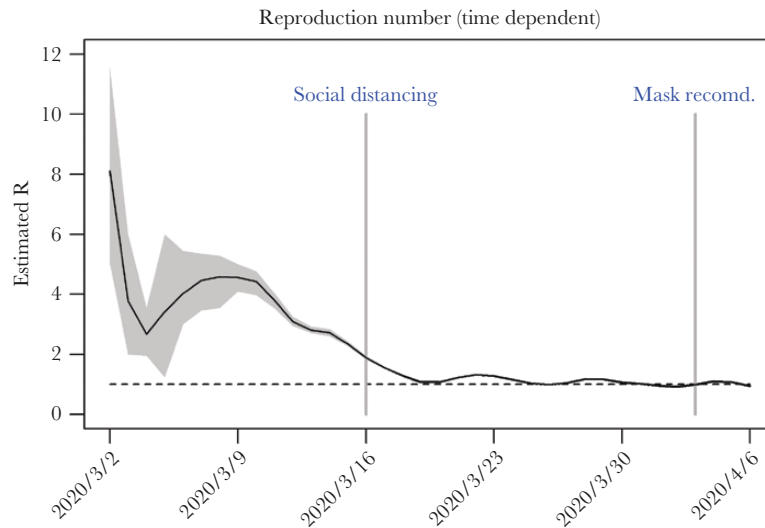
Figure 5. Reproduction number based on laboratory-confirmed coronavirus disease 2019 cases in NYC on a timeline (time-dependent).

of the host population that is susceptible). Here $R_0 \propto aS_0/b$ (a refers to a proportionality constant; S_0 refers to an initial susceptible population, b refers to the recovery rate among the infected population) and a = p*q (where p refers to the contact frequency and q refers to the effective attack rate). Almost all interventions of infectious diseases in terms of epidemiological dynamics focus on reducing the coefficient of transmission to lower the contact frequency and reduce the attack rate. Social distancing can reduce both the contact frequency and the attack rate, while cloth face coverings can dramatically reduce the attack rate. A previous study pointed out that respiratory pathogens can spread 6 meters through cough and 8 meters through sneezing [21]. It is known that aerosol of the virus in a confined space can remain for a long time and spread even further. Hence, social distancing alone may not fully eliminate the chance of spread of the infection. Clothing coverings can further reduce potential transmission from presymptomatic and asymptomatic carriers who contribute to SARS-CoV-2 spread [22]. However, cloth face covering is not equal to an N95 mask. Moreover, even an N95 mask cannot prevent other types of virus transmission such as through conjunctiva [23, 24]. Also, usually only a certain amount of people follow these types of population-level recommendations and restrictions. Recent data from NYC show that 90% of the population complied with the recommendation [25]. Of note, these 2 interventions might not control indirect transmission, which plays a role in the spread of SARS-CoV-2 [3]. To prevent indirect transmission, hand washing and avoiding confined spaces are the best nonpharmaceutical interventions that can be undertaken at the individual level. All of the above, including indirect transmission, could partly explain why the R_t did not diminish to 0 after implementation of these 2 measures.

A study from Germany indicated that face masks reduced the daily growth rate of reported infections by around 40% and

assessed the credibility of the various estimates [20]. Of note, in Germany, face masks became compulsory in public transport and sales shops early on in the pandemic [20], whereas in the United States people struggled with face mask guidelines due to inconsistent information on whether the general public needed to wear a mask in public places, as well as how to secure a face mask covering [26]. However, during this time, even when face mask guidelines were not in place in the United States, social distancing guidelines were already in place.

To the best of our knowledge, no survey data have been published on masking proficiency in the population of COVID-19 patients in the United States. However, according to a survey in the United States after Hurricane Katrina, only 24% of participants demonstrated proper technique when they donned masks for mold remediation. A cross-sectional study from Singapore reported on the proficiency of people in public in Singapore in wearing N95 masks (duck-bill foldable N95 mask, 3M VFlex 9105). Among 714 participants in this Singapore study, only 90 participants (12.6%; 95% CI, 10.3%–15.3%) passed the Visual Mask Fit Test Pass test [26]. People have struggled with face mask guidelines, especially in the United States, due to the inconsistent information on whether the general public needs to wear a mask in public spaces, as well as access to the recommended coverings [27].

Regarding social distancing, according to an online survey in the United States in the early stages of the pandemic, only 39.8% of respondents reported not complying with social distancing recommendations in the middle of March (among 20 734 responses) [24]. Of note, this study only refers to social distancing and does not include masking. Further, the study was conducted via an online survey and did not include NYU, the center of the pandemic during that period. Also, compared with youth, this survey found that the elderly were less likely to participate in the survey, likely due to its being administered online.

Intervention time, measurement degree, and length of intervention implemented are 3 factors that play a key role in the prevention and control of COVID-19. Our results from this study confirm results from previous studies, that the timeline for implementing the interventions is of the same, if not greater, importance as the scale of the implemented interventions [28]. There was a long time window before the spike of COVID-19 cases caused by exponential growth of infections. Although aggressive intervention measurements such as isolation or door-to-door shut down could rapidly decrease confirmed COVID-19 cases [16, 29, 30], the impact of these measurements on other aspects of life such as economic needs should be also considered. For example, 1 study indicated that the median daily R_t in Wuhan declined from 2.35 (95% CI, 1.15–4.77) at 1 week before travel restrictions were introduced on January 23, whereas it was 1.05 (95% CI, 0.41–2.39) 1 week after [31]. The reduction due to travel restrictions in that study is similar to the reduction due to cloth face coverings in the current study. However, these 2 measurements have different societal impacts. Hence, when choosing appropriate interventions for infectious disease control, health policy makers need to balance between public health concerns and the social and economic influences that result from the restrictions put in place.

The incubation period ranged from 2 to 14 days. It varied among the population, and the median incubation period was ≃3.0 days [32]. In addition, in the early stage of the COVID-19 pandemic in NYC, there were delays and latencies in testing. On the other hand, daily travel and person-to-person interaction habits may have already been affected, partially due to dissemination of COVID-19 information on the internet and through traditional news media. Thus, the exact time point of the mask policy's effect is hard to determine. Additionally, as there is a lack of such studies and data, we decided for the purposes of this study to use the policy declaration date.

Our study has several limitations. First, the limitations of the emerging situation make it less likely to conduct a well-controlled experiment. Second, estimates of the parameters used relied on the limited information available from the early stages of the outbreak in NYC. There might be 2 waves of imported COVID-19 cases in NYC, 1 from China and 1 from Europe, respectively. Third, due to the context of the model assumptions, generalization of the results from the current study to the population outside of NYC may be limited. Fourth, other potential risk factors, such as age and gender, have not been collected and/or were not available, and thus were not considered in the model. Fifth, starting on March 31, numbers of COVID-19 cases were reported by diagnosis date instead of report date. Although the diagnosis date may improve the accuracy when people are getting sick and being tested compared with the report date, this change could result in data mismatch. Sixth, our current study only included laboratory-confirmed cases, which might underestimate total COVID-19 cases. This is partially because most asymptotic carriers could not access the laboratory test due to absence of symptoms, which was a prescreening requirement to receive the test, particularly in the early stages of the COVID-19 pandemic in the United States when testing was more limited. As these estimates are refined, our model can be reparametrized to provide more accurate projections. More studies are needed for improving our understanding of the effectiveness of various types of cloth face coverings and for better educating the public about intervention approaches during this and future infectious disease outbreaks. Seventh, the SEIR model used in our study is a relatively basic epidemiological model, which may not contain the structures possessed by some recently developed models. This is partially due to the availability of data and complexity/uncertainty in factors contributing to the magnitude of attack rates. We conducted analyses based on a range of values for attack rate–related measures. We will further evaluate/monitor models/data availability and plan to include relevant analyses in future studies. Lastly, it is true that the most presented COVID-19 modeling was based on some parameters from previous pandemic experience, especially respiratory diseases such as SARS. This is partially because those emerging infectious diseases have similar patterns, not only in epidynamics, but also in the controlling methods to reduce and stop disease spread. Certain key parameters can be more accurately estimated after a pandemic ends. However, with the COVID-19 pandemic ongoing, we must draw on lessons learned from other similar diseases and the currently available information. The data in the presented study were from the official website of NYC, which should reflect the actual pandemic in NYC at the time the study was conducted.

Our study has the potential to shed light on the current COVID-19 pandemic in several ways. It indicates that nonpharmaceutical measures applied in NYC such as social distancing and cloth face coverings are effective in controlling the spread of COVID-19. It provides valuable insight for other cities and countries experiencing COVID-19.

CONCLUSIONS

Our findings highlight that social distancing and cloth face coverings are effective in reducing the spread of SARS-CoV-2. These interventions led to a decline in the number of COVID-19 patients in NYC. This study further highlights the need for clear and consistent messaging and communication in times of an emergency such as COVID-19. For emerging infectious diseases, quick responses based on solid scientific evidence, including evaluating and choosing proper intervention strategies and implementation plans, are necessary. The most aggressive and rigorous interventions may not always be based on the scientific evidence, and as a result may not have the largest and most efficient impact on infection reduction.

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