Identifying airborne transmission as the dominant route for the spread of COVID-19

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Various mitigation measures have been implemented to fight the coronavirus disease 2019 (COVID-19) pandemic, including widely adopted social distancing and mandated face covering. However, assessing the effectiveness of those intervention practices hinges on the understanding of virus transmission, which remains uncertain. Here we show that airborne transmission is highly virulent and represents the dominant route to spread the disease. By analyzing the trend and mitigation measures in Wuhan, China, Italy, and New York City, from January 23 to May 9, 2020, we illustrate that the impacts of mitigation measures are discernable from the trends of the pandemic. Our analysis reveals that the difference with and without mandated face covering represents the determinant in shaping the pandemic trends in the three epicenters. This protective measure alone significantly reduced the number of infections, that is, by over 78,000 in Italy from April 6 to May 9 and over 66,000 in New York City from April 17 to May 9. Other mitigation measures, such as social distancing implemented in the United States, are insufficient by themselves in protecting the public. We conclude that wearing of face masks in public corresponds to the most effective means to prevent interhuman transmission, and this inexpensive practice, in conjunction with simultaneous social distancing, quarantine, and contact tracing, represents the most likely fighting opportunity to stop the COVID-19 pandemic. Our work also highlights the fact that sound science is essential in decision-making for the current and future public health pandemics.

COVID-19 | virus | aerosol | public health | pandemic

The novel coronavirus outbreak, coronavirus disease 2019 (COVID-19), which was declared a pandemic by the World Health Organization (WHO) on March 11, 2020, has infected over 4 million people and caused nearly 300,000 fatalities over 188 countries (1). Intensive effort is ongoing worldwide to establish effective treatments and develop a vaccine for the disease. The novel coronavirus, named as severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), belongs to the family of the pathogen that is responsible for respiratory illness linked to the 2002–2003 outbreak (SARS-CoV-1) (2). The enveloped virus contains a positive-sense single-stranded RNA genome and a nucleocapsid of helical symmetry of ∼120 nm. There exist several plausible pathways for viruses to be transmitted from person to person. Human atomization of virus-bearing particles occurs from coughing/sneezing and even from normal breathing/talking by an infected person (3–6). These mechanisms of viral shedding produce large droplets and small aerosols (3), which are conventionally delineated at a size of 5 μm to characterize their distinct dispersion efficiencies and residence times in air as well as the deposition patterns along the human respiratory tract (3, 7). Virus transmission occurs via direct (deposited on persons) or indirect (deposited on objects) contact and airborne (droplets and aerosols) routes (3). Large droplets readily settle out of air to cause person/object contamination; in contrast, aerosols are efficiently dispersed in air. While transmission via direct or indirect contact occurs in a short range, airborne transmission via aerosols can occur over an extended distance and time. Inhaled virus-bearing aerosols deposit directly along the human respiratory tract.

Previous experimental and observational studies on interhuman transmission have indicated a significant role of aerosols in the transmission of many respiratory viruses, including influenza virus, SARS-CoV-1, and Middle East Respiratory Syndrome coronavirus (MERS-CoV) (8–11). For example, airborne coronavirus MERS-CoV exhibited strong capability of surviving, with about 64% of microorganisms remaining infectious 60 min after atomization at 25 °C and 79% relative humidity (RH) (9). On the other hand, rapid virus decay occurred, with only 5% survival over a 60-min procedure at 38 °C and 24% RH, indicative of inactivation. Recent experimental studies have examined the stability of SARS-CoV-2, showing that the virus remains infectious in aerosols for hours (12) and on surfaces up to days (12, 13).

Several parameters likely influence the microorganism survival and delivery in air, including temperature, humidity, microbial resistance to external physical and biological stresses, and solar ultraviolet (UV) radiation (7). Transmission and infectivity of airborne viruses are also dependent on the size and number concentration of inhaled aerosols, which regulate the amount (dose) and pattern for respiratory deposition. With typical nasal breathing (i.e., at a velocity of $\sim 1\ m \cdot s^{-1}$) (4), inhalation of airborne viruses leads to direct and continuous deposition into the human respiratory tract. In particular, fine aerosols (i.e., particulate

Significance

We have elucidated the transmission pathways of coronavirus disease 2019 (COVID-19) by analyzing the trend and mitigation measures in the three epicenters. Our results show that the airborne transmission route is highly virulent and dominant for the spread of COVID-19. The mitigation measures are discernable from the trends of the pandemic. Our analysis reveals that the difference with and without mandated face covering represents the determinant in shaping the trends of the pandemic. This protective measure significantly reduces the number of infections. Other mitigation measures, such as social distancing implemented in the United States, are insufficient by themselves in protecting the public. Our work also highlights the necessity that sound science is essential in decision-making for the current and future public health pandemics.

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We interpreted the differences in the pandemic trends by considering the mitigation measures implemented worldwide. The curve flattening in China can be attributed to extensive testing, quarantine, and contact tracing; other aggressive measures implemented in China include lockdown of all cities and rural areas in the whole country, isolation of residents having close contact with infected people, and mandated wearing of face masks in public. However, the effectiveness of those mitigation measures has yet to be rigorously evaluated. Differentiation of the effects of those mitigation measures in China is challenging (19), since the implementation occurred almost simultaneously in January 2020. While similar quarantine, isolation, and city lockdown measures were also implemented on March 9 in Italy after the country became the second epicenter, the curve of infections has yet to show complete flattening. In the United States, guidelines for social distancing, quarantine, and isolation were issued by the federal government on March 16, and stay-at-home orders were implemented by many state and local governments starting, for example, on March 19 and April 3 and on March 22 in NYC. The social distancing measures implemented in the United States include staying at least 6 feet (~2 m) away from other people, no gathering in groups, staying out of crowded places, and avoiding mass gatherings (20). Obviously, the continuous rise in the US infected numbers casts doubt on the effectiveness of those preventive measures alone (Fig. 1 *B* and *C*).

In contrast to China, wearing of face masks was not mandated and was unpopular in most of the western world during the early outbreak of the pandemic. Advice on the use of face masks was not issued until April 6, 2020 by the WHO (1), claiming that it is important only to prevent infected persons from viral transmission by filtering out droplets but that it is unimportant to prevent uninfected persons from breathing virus-bearing aerosols. The regions heavily plagued by COVID-19 in northern Italy, such as Lombard, ordered face covering in public starting on April 6, and the Italian authorities required nationwide mandatory use of face masks on May 4. All New Yorkers were mandated to use face covering in public starting on April 17, when social distancing was not possible. With measures implemented in the United States seemingly comparable to those in China, social distancing, quarantine, and isolation exhibited little impact on stopping the spreading of the disease in the United States, as reflected by the linearity from April 1 to May 9 (Fig. 1*C*). It is possible, however, that these measures likely alter the slope of the infection curve, that is, by reducing the rate of infections during the early stage of the pandemic (Fig. 1). Notably, the recommended physical separation for social distancing is beneficial to prevent direct contact transmission but is insufficient (without face masks) to protect inhalation of virus-bearing aerosols (or even small droplets at intermediate proximity), owing to rapid air mixing (7).

Understanding the Impacts of Face Covering

Compared to the simultaneous implementation of measures in China, intervention measures were successively implemented in the western world (Fig. 2*A*), providing an opportunity for assessing their relative effectiveness. We quantified the effects of face covering by projecting the number of infections based on the data prior to implementing the use of face masks in Italy on April 6 and NYC on April 17 (Fig. 2*A*; see *Methods*). Such projections are reasonable considering the excellent linear correlation for the data prior to the onset of mandated face covering (Fig. 2 *B* and *C* and *SI Appendix*, Fig. S1). Our analysis indicates that face covering reduced the number of infections by over 78,000 in Italy from April 6 to May 9 and by over 66,000 in NYC from April 17 to May 9. In addition, varying the correlation from 15 d to 30 d prior to the onset of the implementation reveals little difference in the projection for both places, because of the high correlation coefficients (*SI Appendix*, Fig. S1). Notably, the trends of the infection curves in Italy and NYC contrast to those in the world and in the United States (Fig. 1*C*), which show little deviation from the linearity due to the nonimplementation of face-covering measures globally and nationally, respectively. The inability of social distancing, quarantine, and isolation alone to curb the spread of COVID-19 is also evident from the linearity of the infection curve prior to the onset of the face-covering rule in Italy on April 6 and in NYC on April 17 (Fig. 2 *B* and *C*). Hence, the difference made by implementing face covering significantly shapes the pandemic trends worldwide.

We further compared the numbers of daily new cases between NYC and the United States (excluding the data in NYC) from March 1 to May 9 (Fig. 3). The daily numbers of newly confirmed infections in NYC and the United States show a sharp increase in late March and early April. There exists a slower increase in the number after implementation of the stay-at-home order (about 14 d in New York and shortly after April 3 in the United States), which is attributable to the impacts of this measure. After April 3, the only difference in the regulatory measures between NYC and the United States lies in face covering on April 17 in NYC. We applied linear regression to the data between April 17 and May 9 in NYC and between April 5 and May 9 in the United States. While the daily numbers of newly confirmed infections fluctuate considerably, the slope of the regression unambiguously reflects the trend in both data. The daily new infection in NYC decreases with a slope of 106 cases per day after April 17, corresponding to a decreasing rate of ~3% per day (relative to April 17). For comparison, the daily new infections in the United States (excluding NYC) increase, with a slope of 70 cases per day after April 4, corresponding to an increasing rate of ~0.3% per day (relative to April 5). Hence, the decreasing rate in the daily new infections in NYC with mandated face covering is in sharp contrast to that in the United States with only social-distancing and stay-at-home measures, further confirming the importance of face covering in intervening the virus transmission.

Dominant Airborne Transmission

We further elucidated the contribution of airborne transmission to the COVID-19 outbreak by comparing the trends and mitigation measures during the pandemic worldwide and by considering the virus transmission routes (Fig. 4). Face covering prevents both airborne transmission by blocking atomization and inhalation of virus-bearing aerosols and contact transmission by blocking viral shedding of droplets. On the other hand, social distancing, quarantine, and isolation, in conjunction with hand sanitizing, minimize contact (direct and indirect) transmission but do not protect against airborne transmission. With social distancing, quarantine, and isolation in place worldwide and in the United States since the beginning of April, airborne transmission represents the only viable route for spreading the disease, when mandated face covering is not implemented. Similarly, airborne transmission also contributes dominantly to the linear increase in the infection prior to the onset of mandated face covering in Italy and NYC (Fig. 2 *B* and *C* and *SI Appendix*, Fig. S1). Hence, the unique function of face covering to block atomization and inhalation of virus-bearing aerosols accounts for the significantly reduced infections in China, Italy, and NYC (Figs. 1–3), indicating that airborne transmission of COVID-19 represents the dominant route for infection.

Recent measurements identified SARS-Cov-2 RNA on aerosols in Wuhan's hospitals (18) and outdoor in northern Italy (21), unraveling the likelihood of indoor and outdoor airborne transmission. Within an enclosed environment, virus-bearing aerosols from human atomization are readily accumulated, and elevated levels of airborne viruses facilitate transmission from person to person. Transmission of airborne viruses in open air is subject to

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