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RESEARCH ARTICLE

Transportation, germs, culture: a dynamic graph model of COVID-19 outbreak

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***Background*: Various models have been applied to predict the trend of the epidemic since the outbreak of COVID-19.**
***Methods*: In this study, we designed a dynamic graph model, not for precisely predicting the number of infected cases, but for a glance of the dynamics under a public epidemic emergency situation and of different contributing factors.**
***Results*: We demonstrated the impact of asymptomatic transmission in this outbreak and showed the effectiveness of city lockdown to halt virus spread within a city. We further illustrated that sudden emergence of a large number of cases could overwhelm the city medical system, and external medical aids are critical to not only containing the further spread of the virus but also reducing fatality.**
***Conclusion*: Our model simulation showed that highly populated modern cities are particularly vulnerable and lessons learned in China could facilitate other countries to plan the proactive and decisive actions. We shall pay close attention to the asymptomatic transmission being suggested by rapidly accumulating evidence as dramatic changes in quarantine protocol are required to contain SARS-CoV-2 from spreading globally.**

Keywords: dynamic graph model; transportation; COVID-19; SARS-CoV-2

Author summary: We designed a dynamic graph model for a glance of the dynamic under the COVID-19 pandemic by considering a transportation model as the center. We illustrated that the asymptomatic transmission is the dominating factor contributing to the outbreak and city lockdown is the most effective way to halt virus spread. In addition, the external medical aids are able to effectively reduce the fatality rate when the city medical system is overwhelmed.

INTRODUCTION

Since the outbreak of 2019 novel coronavirus (SARS-CoV-2), the fast-moving spread has killed over 18,000 people and infected more than 413,000 globally (as of Mar. 25, 2020) [1]. Various models have been applied to predict the trend of the epidemic [2–6]. However, major factors such as transportation and cultural customs as well as city lockdown have not been weighed sufficiently. In this study, we designed a dynamic graph model, aiming not to precisely predicting the number of infected cases, but to a glance the dynamics under a public epidemic emergency situation and different contributing factors. Our model and simulation may provide perspectives to public health authorities around the world for better informed preventive and containment actions.

RESULTS

Quarantine strategies affect virus transmission

Using the dynamic graph model designed for this outbreak (Methods), we first simulated the spread of the virus from one patient and compared the outcomes of different quarantine strategies. As shown in Fig. 1A, the strategy of quarantining individuals demonstrating fever symptoms does slow down the spread of the virus significantly compared to "no quarantine". However, it is insufficient to contain the spread if no further interventions are implemented. Although it certainly costs more resources to quarantine everyone with detectable virus RNA, this strategy does contain the spread effectively. In addition, if we quarantine only infected individuals with fever symptom, we found that among the newly infected individuals, the proportion contributed to asymptomatic transmission is greater than that of symptomatic transmission (Fig. 1B). Although symptomatic individuals may have much higher virus load than asymptomatic ones, they are easier to detect and grounded by quarantine or simply too weak to travel around to spread the virus further. In contrast, asymptomatic individuals may have much lower virus loads but as they actively move around and interact with uninfected individuals, they may contribute to more infections. Thus, it is imperative for countries to adopt this conservative strategy of quarantine symptomatic ones, which might become the next hot spots of COVID-19 outbreak.

Effects of city transportation and confined spaces

Since an infected individual potentially transmits the virus to a healthy one during close contacts within a confined space such as a shared transportation vehicle, we next simulated scenarios of typical cities around the world with different compositions of transportation means as well as various types and densities of confined spaces such as cinemas, restaurants and bars. For example, in Wuhan, the capital of Hubei province, shared transportations (family cars, buses, subways and taxis) are commute options at daily basis and the amount of public places is modest. However, a modern city like Paris would have a higher percentage of individuals commuting by public transportations. For comparison, we also used data from several other world cities (Supplementary Table S1): Tokyo, Los Angeles, Singapore and Yinchuan, in analysis. As shown in Fig. 2A, our simulation suggested densely populated cities like Paris, Tokyo and Singapore with advanced public transportation and plenty of popular public places were particularly vulnerable to the viral transmission while general population in US cities like Los Angles commuting via family cars significantly reduced the risk of virus transmission. Furthermore, limited public transportation in an underdeveloped city like Yinchuan effectively halted virus transmission. This indicates that although convenient public transportation and popular social gathering places in modern cities may provide enjoyable living styles, unfortunately, also facilitates rapid transmission of infectious diseases.

We also evaluated how social gatherings activities

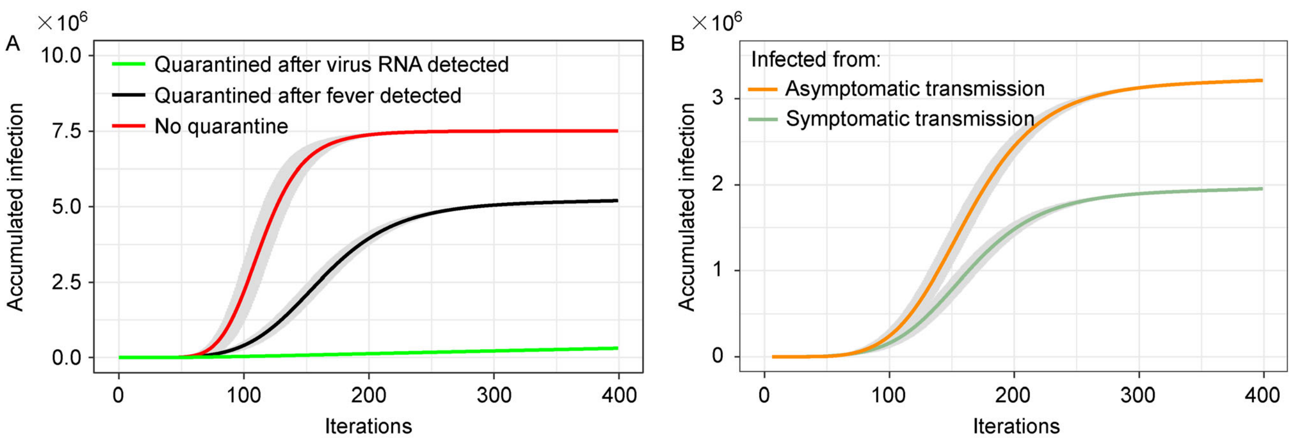

Figure 1. The relations between virus spreading and quarantine strategy. (A) Different quarantine strategies result in different epidemic outcomes. (B) Contribution to infection from symptomatic transmission vs. asymptomatic transmission when individuals with fever are placed in quarantine sites.

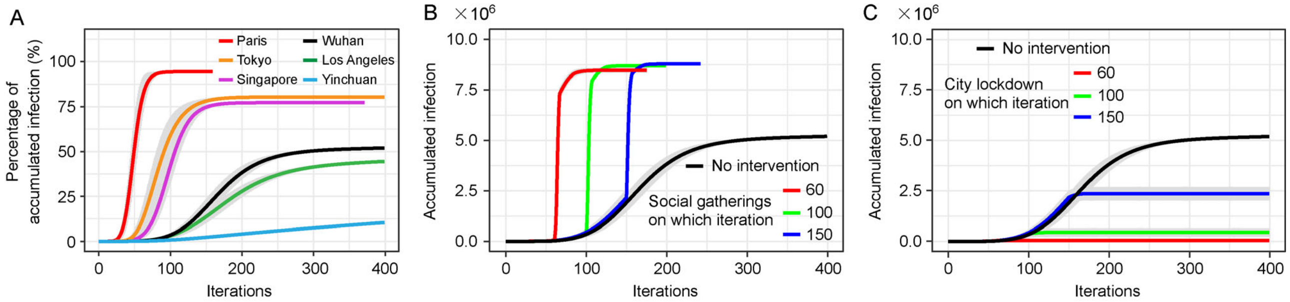

Figure 2. Impact of transportation and confined space in virus spread. (A) Virus spreading in cities with different quantities and compositions of public transportation and confined space. (B) Large scale social gatherings speed up the viral spread. (C) City lockdown halts transmission drastically. All these simulations are under a strategy of quarantine after fever detected. The population and transportation data sources are shown in Supplementary Table S2.

affected the spread of disease. The coronavirus epidemics outbroke around the Chinese New Year or Spring Festival, a traditional Chinese festival when relatives visit each other after the first day of Chinese New Year, which may continue for one week. We simulated the effect of family and relative gatherings during Spring Festival and examined how those activities would facilitate the spread of the virus. In addition, people rushed to hospitals for diagnoses soon after a lockdown of Wuhan city was announced. As shown in Fig. 2B, earlier gatherings would stimulate a wider spread of the virus, consistent with previous report that the hospital gatherings contributed to 41.3% of all infections [7]. Fortunately, Chinese civilians were warned about the severe consequence of social gatherings during COVID-19 outbreak and as a result most people stayed at home during the whole Chinese New Year period for at least 15 days.

It is unusual to lockdown big cities, an extreme act to halt an epidemic. We found that city lockdown (Fig. 2C) halts transmission of virus immediately and the earlier installation of those measures the lower maximum number of infected cases. Tian *et al.* predicted that a delay of 2.91 days of the outbreak would be observed in other major cities compared to Wuhan [4]. However, the spread of the virus became under control and Chinese authorities started to gradually lift city lockdown outside Hubei province and resume economic activities, confirming the effect of city lockdown predicted by our dynamic graph model. Although lockdown of the cities is a radical administrative action with a major impact on the economy, such a decisive action by Chinese authorities have certainly minimized further spreading of the virus within Wuhan and other major Chinese cities.

Effects of imported infections and external medical aids

Having evaluated the effects of situations and control strategies within a city, we next investigated the impact of imported infected cases between cities and relocation of medical aid on the spread of the virus and the fatality rate (Fig. 3). There were over five million people leaving Wuhan during Spring Festival Travel Rush right before the city lockdown. Although most of them went to nearby small cities in the same province, a significant proportion did travel to other Chinese cities. The sudden arrival of infected cases posed a burden to medical systems in small cities and quickly consumed rather limited local medical resources under the virus outbreak of this magnitude. As expected, the more imported infected cases, the more difficult to contain the spread (Fig. 3A). Even being a large city of 14 million population and the capital of Hubei province, Wuhan could not handle such a large number of infected ones, causing a much higher fatality rate due to the overload of medical workers and shortage of medical devices. Thus, Chinese authorities recently encouraged the massive production of medical supplies and mobilized thousands of medical workers from less affected domestic cities to help patients in Wuhan and nearby cities. With tens of new quarantine sites being built and dormitories in several universities being expropriated, not only patients with severe symptoms could be better treated in ICU rooms but also those with minor symptoms could be screened and transported to quarantine sites to avoid further spread. According to our simulation, with the increase of hospital ICUs, fatality rate will drop significantly (Fig. 3B), which we do hope to observe in Wuhan in coming days.

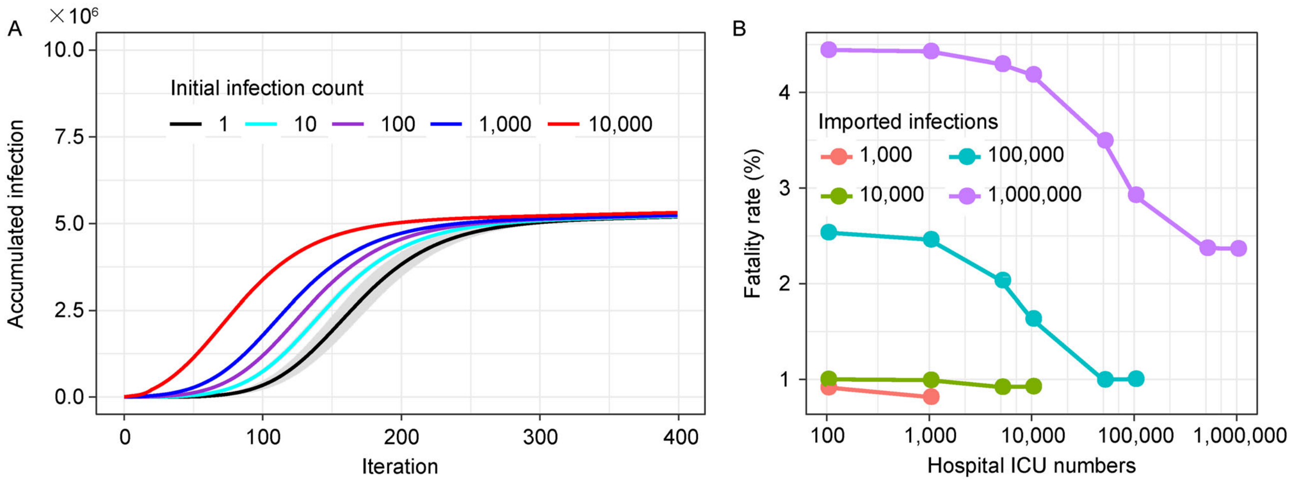

Figure 3. Imported infections and medical aid affect the spreading and fatality rate. (A) The impact of imported infected cases to the spread of the virus. (B) Medical aid reduces the fatality rate. All these simulations are under the strategy of quarantine after fever detected.

DISCUSSION

Taken together, we designed and implemented a dynamic graph model to simulate SARS-CoV-2 spread within and between cities. This model is largely a physical model to incorporate various factors like transportation means with diverse capacities and close contact probabilities, which is different from classical SIR model that are built on mathematical equations [8,9]. Moreover, this dynamic graph model does not aim to predict precise numbers of infections overtime but to illustrate the contributions of various factors affecting the spread.

We demonstrated the impact of asymptomatic transmission in this outbreak and showed the effectiveness of city lockdown to halt virus spread within a city. We also illustrated how sudden arrival of a large number of cases could overwhelm the medical system in a city and external medical aid is critical to not only containing further spread but keeping fatality rate low. It is alarming that highly populated modern cities are particularly vulnerable and therefore we shall closely monitor the developing situation in Japan and South Korea. From our model simulation, the proactive and decisive actions taken by authorities in China, the primary battleground of COVID-19, who gradually increased the alert level and adopted a more radical set of measurements once the situation escalated, should serve as a successful experience for countries facing similar or worse epidemics. Admittedly, it is wrong to lockdown the whole country once a single case is detected. However, it is potentially devastating to treat COVID-19 as regular flu because the fatality rate does differ and a large number of hard-to-treat severe cases overwhelms the medical system of any city within weeks if the spread is not controlled at a low level. We also recommend that CDC (center of disease control) or equivalent authorities in all countries shall pay close attention to the asymptomatic transmissions and dramatic changes in quarantine protocols are required to contain SARS-CoV-2 from spreading globally.

METHODS

Similar to a graph model developed by Guo [10] to model the pandemic spreading based on spatial interaction data, we designed a dynamic graph model (Fig. 4A) centered at transportation module as people in a city take various local transportations to commute between confined spaces, considering that close-distance contacts during transportation and inside confined spaces are likely the most important factors aiding coronavirus transmission from the infected to the healthy ones. We built separate nodes with different numbers of seats and various virus transmission rates, accounting for residential exposure and transportation exposure such as private car, taxi, bus, subway and walking (Fig. 4B, Supplementary Table S2). Around the transportation module, we placed stationary residential areas, public places and hospitals as three major categories of nodes with a typical number of individuals and various virus transmission probabilities (Fig. 4A, Supplementary Table S2). Finally, we attached the node of quarantine sites to hospitals. In each public or residential area and each transportation, social network among individuals will be constructed by the social activities. Once an infected individual with or without symptoms is present in a network, he/she will spread the virus to the others by connections (Fig. 4B, Supplementary Materials).

During each iteration of the simulation, a random

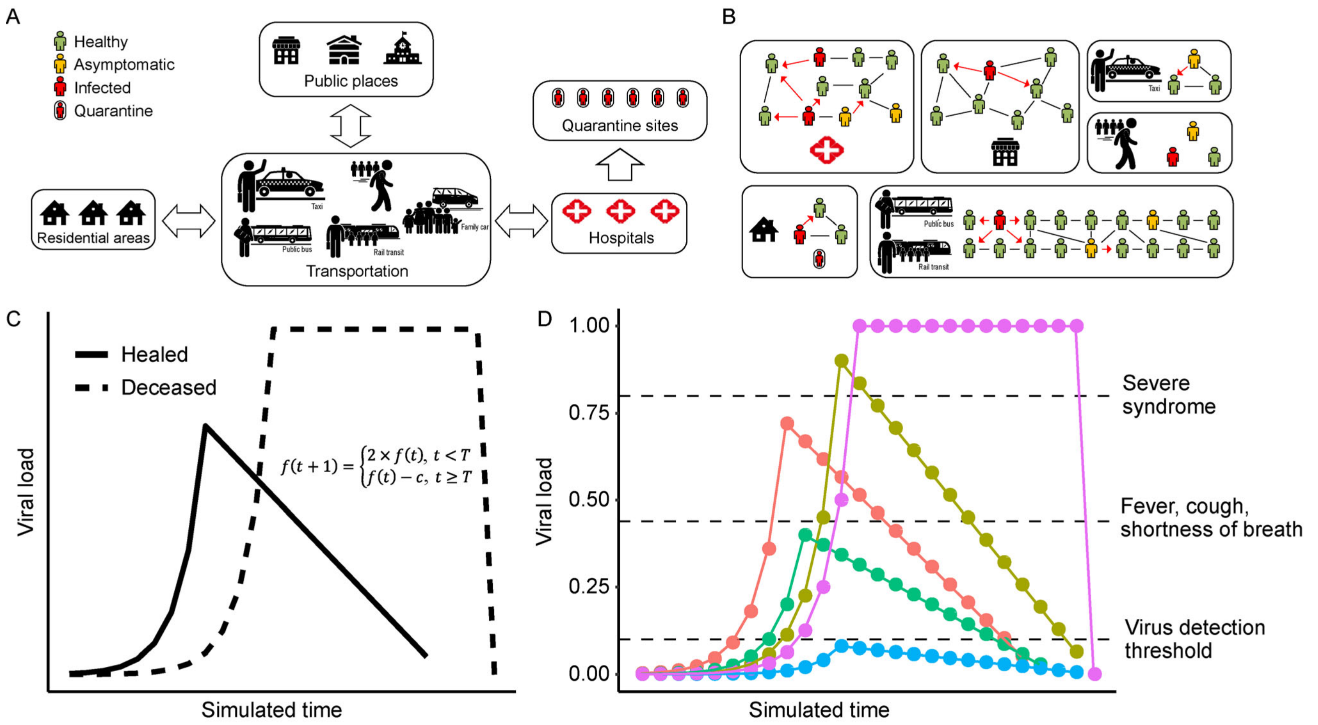

Figure 4. The dynamic graph model of virus spread. (A) The diagram of the dynamic graph model. (B) The details of spreading network in each confined place and transportation. (C) The formula of viral load in each infection. *T* is the incubation period, and *c* is a constant value. For deceased patients, *c* is set as zero. (D) Examples of infection with different maximum virus load and their corresponding clinical symptoms.

selection of individuals would start from one residential area, travel through the routes defined by graph structure and return to the starting residential area. Once a symptom appears (Supplementary Materials), the infected individuals would travel to hospitals and remain at either a hospital or a quarantine site if space allows. Otherwise, they will return to residential areas and stay at home unless further screening or quarantine is simulated. Healthy individuals might become infected according to the product of infection probability and spreading probability once close contacting with an infected person in the same vehicle or confined space as Eq. (1) (Supplementary Materials).

$$p = p_S' \times p_I \tag{1}$$

where p_S' is the spreading probability positively correlated to the virus load (Fig. 4C) and p_I is the infection probability setting as 0.1 according to the Chinese CDC news.

Although the major risk of getting infected stems from unprotected exposure to a patient with symptoms and diagnosed SARS-CoV-2 infection, the role of asymptomatic or pre-symptomatic transmission has been suspected but remains unconfirmed due to lack of quantification [11–13]. Accumulating data suggests that SARS-CoV-2 RNA is detectable in biopsies from both upper and lower respiratory tract [14]. It has been reported by Chinese CDC that disease severity and mortality rate are positively correlated to age of the patient, a sign of possible higher percentage of young infected patients being mild or even asymptomatic [15]. Thus, we argue that before adaptive immune system acts, the virus may multiply rapidly upon its entry via oral mucosa and the infection may spread from upper to lower respiratory tract, especially in immunocompromised patients. Once adaptive immune system initiates, the virus load may decline gradually. The function of virus load is defined as Eq. (2) (Supplementary Materials).

$$f(t+1) = \begin{cases} 2 \times f(t), & t < T \\ f(t) - c, & t \geqslant T \end{cases} \tag{2}$$

where *T* is the length of incubation period, *c* is a constant value.

As shown in Fig. 4C and D, for one newly infected individual, we first assigned the length of incubation period according to the distribution of incubation durations reported in a cohort of more than 1,000 patients [16] and randomly set the maximum virus load between

0 and 1 (Supplementary Materials). The virus load started small from a low-level upon infection and grew before reaching a specific viral peak in a given individual during the incubation period, then it declined to elimination in healed individuals or remained at the peak level for the deceased, as Eq. (2) depicts. With this simplified way of simulating virus load during the time course of infection, we aimed to mimic various scenarios ranging from very minor (infected but virus RNA remained undetected, blue dotted line in Fig. 4D) to mild (virus RNA detected but without any symptom, green dotted line in Fig. 4D) and eventually symptomatic or severe cases. Notably, this virus load simulation is tuned towards the reported properties of COVID-19 [16] and could be adjusted for other infection agents. We set the virus spreading probability equal to the virus load in this patient. We simulated the transmission of the virus with a certain number of initially infected individuals and observed the spread of the virus in various scenarios.

SUPPLEMENTARY MATERIALS

The supplementary materials can be found online with this article at https://doi.org/10.1007/s40484-020-0215-4.

CODE AVAILABILITY

https://github.com/xjtu-omics/2019-nCoV_graph_model.

AUTHOR CONTRIBUTIONS

K.Y. conceived of and designed the study. X.Y. and T.X. implemented the code. X.Y. and P.J. collected and analyzed the data. K.Y., X.Y., H.X., L.Z., L.G. interpreted the results. X.Y. produced the figures. K.Y., X.Y. and L.G. drafted the Article. All authors contributed to the writing of the final version of the Article.

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COMPLIANCE WITH ETHICS GUIDELINES

The authors Xiaofei Yang, Tun Xu, Peng Jia, Han Xia, Li Guo, Lei Zhang and Kai Ye declare that they have no conflict of interests.

All procedures performed in studies were in accordance with the ethical standards of the institution or practice at which the studies were conducted, and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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