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Pandemic risk of COVID-19 outbreak in the United States: An analysis of network connectedness with air travel data

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\textbf{A B S T R A C T}

\textbf{Objectives:} The United States has become the country with the largest number of COVID-19 reported cases and deaths. This study aims to analyze the pandemic risk of COVID-19 outbreak in the US.

\textbf{Methods:} Time series plots of the network density, together with the daily reported confirmed COVID-19 cases and flight frequency in the five states in the US with the largest numbers of COVID-19 cases were developed to discover the trends and patterns of the pandemic connectedness of COVID-19 among the five states.

\textbf{Results:} The research findings suggest that the pandemic risk of the outbreak in the US could be detected as early as the beginning of March. The signal was prior to the rapid increase of reported COVID-19 cases and flight reduction measures. Travel restriction can be strengthened at an early stage of the outbreak while more focus of local public health measures can be addressed after community spread.

\textbf{Conclusions:} The study demonstrates the application of network density on detection of pandemic risk and its relationship with air travel restriction in order to provide useful information for policymakers to better optimize timely containment strategies to mitigate the outbreak of infectious diseases.

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\textbf{Introduction}

Coronavirus disease 2019 (COVID-19) has become a worldwide pandemic since early 2020. More than 33 million confirmed cases and one million deaths have been reported over the world by the end of September 2020 (WHO, 2020a). Specifically, the US has recorded the largest number of total confirmed cases and deaths among those affected countries. The first COVID-19 confirmed case was found in the US in late January, and the US federal government had imposed some travel restrictions on foreign nationals within the preceding 14 days (The White House, 2020a). Despite these measures, an exponential growth in the number of infected people was still recorded in late March across various states. The US federal government finally started several social distancing measures commensurate with the pandemic risk in the community (The White House, 2020b), such as the bans on public gathering, closures of public places and inessential business, and quarantine measures. The World Health Organization (WHO) has classified the transmission of COVID-19 in the US as “community transmission” since 09 April 2020 (WHO, 2020a). This happened only in two months after the first COVID-19 case reported in an American citizen (CDC, 2020a).

Community transmission (or community spread) indicates that large-scale local transmissions with an unidentified transmission chain occurred (WHO, 2020b). It is a critical alarm for a country in the early stages of the pandemic because untraceable infection sources would largely obstruct the effectiveness of contact tracing in the surveillance of pandemic connection. Failure in quarantining infection sources would also delay opportunite public health interventions, such as social distancing and environmental cleaning, to block or mitigate further spreading of the virus. Therefore, while the observable infection cases are usually the

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earliest epidemiological data on hand, there is a need for early detection of pandemic risk using these available data before the community transmission occurs.

Given the rapid spread of the pandemic within a short period of time, the investigation of epidemiological data on COVID-19 becomes crucial for exploring possible optimization of outbreak analysis during public health emergencies caused by emerging infectious disease (Gregori et al., 2020; Sun et al., 2020). Although experimental data are reliable for identifying the infectious diseases and their transmission, limited laboratory resource and production of analysis results restrict the extrapolation of those findings to the entire population. Epidemiological data, which refers to the observations under nonexperimental context, serve as vital evidence for analyzing the development of infectious diseases (Ni et al., 2017). Besides, these data are usually associated with a variety of operational data, such as hospitalization data (Gregori et al., 2020; Sun et al., 2020) and transportation data (Bogoch et al., 2015; Eichner et al., 2009; Nishiuma et al., 2020), in order to examine and evaluate the feasibility of different infection control and public health measures.

Network analysis, which has been used for assessing connectedness and systemic risk (Newman, 2018), extends the application to epidemiological studies (Chu et al., 2020a, 2020b; So et al., 2020) to construct COVID-19 pandemic networks over time. Different US states were linked together in the pandemic networks by capturing the common trend in the changes of the confirmed COVID-19 cases in the US states. By studying how dense the pandemic networks are, we are able to assess the pandemic risk dynamically with the use of publicly available data. In addition, by linking network density with air travel data, we may have a better understanding on the effectiveness of air travel restriction in reducing pandemic risk.

Notably, early risk detection on the outbreak of the infectious disease would help to provide more evidence for imposing timely and effective public health measures to mitigate the geographic spread of coronavirus (Rivers et al., 2019). This study aims to investigate the pandemic risk detection using the network density and comparing it with the daily COVID-19 cases and flight frequency in five selected states in the US.

Figure 1. Time series plots of the daily reported confirmed COVID-19 cases in the 5 States in the US, network density, and daily reported flights in 5 States in the US.
Materials and methods

Network density was used in this study for identifying the pandemic connectedness of COVID-19 among the states in the US. Daily reported COVID-19 cases of all 50 states from 15 February to 30 September 2020 were collected from Johns Hopkins University (JHU, 2020) for calculating the network density. Further, data about the reported flights in the five selected states in the US (including New York, Texas, California, Florida, and Georgia) were retrieved from the information provided by The Collaborative Arrangement for the Prevention and Management of Public Health Events in Civil Aviation Program and the Federal Aviation Administration (FAA) airport meta records (CAPSCA, 2020; FAA, 2020). We chose these five states for investigation because they recorded the largest numbers of COVID-19 cases, and hence they were useful for comparing the changes in air travel and the pandemic development within the US. As all the data above are publicly available, no patient consent was needed, and no ethical approval was required.

The connectedness of two states at a specific time $t$ was examined by calculating their correlation of changes in the square-root of the number of confirmed COVID-19 cases in the past 14 days (Chu et al., 2020a). Therefore, the resulting correlations of changes in confirmed COVID-19 infection between two states were calculated from 29 February to 30 September 2020. The value of correlation greater than 0.5 indicates a connection in a pandemic network between two states (So et al., 2020). Then, the network density was further calculated by compiling the ratio of the number of connections to the number of possible connections among all states in the US. Below are the summary steps to find the network density in day $t$. Chu et al. (2020a) provided a more detailed explanation to find the network density.

1 Define $X_{it}$ as the number of confirmed cases of state $i$ in day $t$. Calculate the daily changes in the square-root of newly confirmed cases, that is, $Y_{it} = \sqrt{X_{it}} - \sqrt{X_{it-1}}$. Statistically, the ‘square-root transformation’ is to make the transformed counts more stable.
2 For day $t$, calculate the correlation of $Y_{it}$ and $Y_{jt}$ for state $i$ and state $j$ using the 14-day data, including the past 13 days and day $t$.
3 Define a connection if the correlation is $>0.5$ and count $E_t$ (the number of connections in the pandemic network in day $t$).
4 Calculate the network density in day $t$ as $D_t = \frac{2E_t}{C_t(C_t-1)}$, where $C_t$ is the number of states to construct the pandemic network in day $t$.

Time series plots were used for visualizing the changes of the network density, the trends of daily reported flights, and confirmed COVID-19 cases in the five selected states within the same period (Figure 1). We compared their trends and patterns to investigate the potential association between pandemic progression and air travel in the US.

Results

As illustrated in Figure 1a, the trend of newly reported COVID-19 cases in the five selected states remained low and steady from February to mid-March but increased drastically in late March. However, in the time series plot of the network density (Figure 1b), two sharp peaks are identified on 02 March and 16 March 2020, prior to the rapid growth of the confirmed cases in those states. The two peaks could be considered to be early signals of the pandemic risk of COVID-19 among the states in the US. More alarming is a steady rising trend in the network density since August 2020, signifying possible increasing severity in the pandemic outbreak.

For the trend of daily flights, the reported numbers remained high in all selected states until 12 March 2020, which was the day after the WHO declared COVID-19 a pandemic. Nevertheless, as shown in Figure 1a and c, during the drop of scheduled flights between mid-March and early-April, the number of reported cases in all the five states had already risen gradually while the network density started to drop from the second peak. These reversed trends provided evidence that the coronavirus might largely reduce spreading among the states in the US and that the community transmissions of the COVID-19 might occur within the states.

In April to June, the significant downward trends of new COVID-19 cases were obvious in New York after stopping most of its daily flights, and the network density remained at a relatively low level. However, as the scheduled flights started to resume considering the slow rising of daily flight frequencies from July, the network density showed a slightly increasing trend. This may be a dangerous sign for the increase in pandemic risk in the US.

Discussion

This study demonstrates the application of network density on detecting pandemic risk and its association with air travel data among the states in the US.

While the first peak of the network density occurred at the beginning of March, only a small number of newly reported COVID-19 cases were actually reported in various states. However, the containment measures imposed by the US government tended to only focus on some international travel restrictions on overseas visitors with minimal restriction policies on citizens’ travel and domestic flights in the US. Citizens could still travel across the 50 states by domestic flights or travel to other unrestricted countries that would increase the likelihood of infecting and spreading COVID-19 (CDC, 2020b). With regard to both international or domestic flights, air transportation facilitates the transmission of vector-borne and even airborne infectious diseases among passengers from different origins (Mangili et al., 2015). Centers for Disease Control and Prevention (CDC, 2020b) emphasized that both international and domestic travel should be avoided to minimize the risk of exposure to the virus causing COVID-19. Many studies also supported travel restriction as a notable measure for delaying the disease-spread at the early stages (Cooper et al., 2008; Hollingsworth et al., 2006; Mangili et al., 2015), which allows more time for governments and policymakers to react and prepare necessary interventions and collection of resources (Kernéis et al., 2008). The approach of combining travel restriction and other interventions is also recommended for enhancing the effectiveness in the prevention of a pandemic. Therefore, the first peak of the network density serves as the early alarm for reinforcement of local travel restrictions, risk-based border screening, and promotion of infection risk by air travel that may help to mitigate the risk of COVID-19 outbreak in the US.

The second peak was found on 16 March, where the infection numbers of COVID-19 started to increase among the states. As a result, the US started implementing various public health and social distancing measures in late March. More importantly, the network density decreased stably from the second peak while the newly reported cases increased in all the five states. This combination suggested that the rising infection numbers were not mainly due to the pandemic connectedness among the 50 states but the transmission within the community of each state. This also aligns with the subsequent report from the WHO on 09 April that classified the transmission of COVID-19 in the US as “community transmission” (WHO, 2020a). Therefore, the reverse trends may serve as another indication of the need for strengthening protective measures (WHO, 2020c), such as
personal hygiene and infection prevention and control, to mitigate the community transmission of COVID-19 (WHO, 2020d). Additional public health interventions, such as suspension of classes and encouragement of medical face mask use for the general public, should also be prepared for implementation.

The peaks of the network density represent a high proportion of COVID-19 connections among the states. As they occurred before the significant growth of infection numbers, these peaks could serve as useful signals for early detection of the outbreak risk of the pandemic within the concerned geographic settings (Chu et al., 2020b; So et al., 2020). The integration of the network density and incidence also helps to identify the changes in epidemic progress. This application would provide supportive evidence for governments and policymakers to impose timely responses toward the outbreak of the pandemic disease before community transmission occurs in their country.

Air travel was found to contribute to several global epidemics and pandemics (Finklatter and Bogoch, 2018), including Severe Acute Respiratory Syndrome (SARS) in 2002, Middle East Respiratory Syndrome (MERS) in 2012, and Ebola virus disease (EVD) in 2014. However, the effectiveness of travel restriction is being queried by researchers (Bajardi et al., 2011; Chong and Zee; Finklatter and Bogoch, 2018). Previous studies mainly focused on the association between the data from air travel and the prevalence of infectious disease. Our study provides a more informative insight into the linkage between the trend of air travel and the local connectedness of the pandemic. In the case of COVID-19, our study showed that air travel restriction should be strengthened to block pandemic connectedness among the states during the early stages of the outbreak in the US. Conversely, the changes in air travel become less associated with pandemic connectedness after community transmissions occurred in those states. Rather than reinforce travel restriction, governments should focus more on local infection prevention control and public health measures.

The case of the COVID-19 outbreak in the US exposes the importance of quick containment response to the outbreak of infectious diseases. Tracking the pandemic connectedness becomes crucial for imposing appropriate measures at the right time. Though there are multiple factors influencing COVID-19 transmission, both travel restriction and public health measures are important factors that should be emphasized to mitigate the progression of the epidemic (Chinazzi et al., 2020). This study provides evidence and insights on the application of network density on early detection of pandemic risk and optimization of timely containment strategies to mitigate the risk of outbreak of infectious diseases. The recent rising trend in the network density starting from August 2020 poses an alarming signal that the pandemic risk in the US has increased since August 2020. The increase in the network density and the evolution of the pandemic risk may be due to partially relaxation of travel restrictions, leading to an increase in the daily reported flights since July 2020.

Conclusion

COVID-19 has become a global pandemic. In this study, we associated the time series plots of the network density, daily reported confirmed COVID-19 cases, and flights frequency to analyze the network connectedness and used five states with the largest numbers of COVID-19 cases in the US as examples to indicate the trends in the pandemic risk of the outbreak in the US, which could be detected as early as the beginning of March. We attempted to provide a scale-free and effective tool that can detect the association of the growth in the numbers of infected cases in different states in the US at an early time even when the number of confirmed cases is small and monitor the pandemic risk, progression, and connectedness of states to provide some useful information for policymakers to take suitable measures at the right time. However, as COVID-19 confirmed cases are affected by multiple factors, especially social distancing during community transmission, we cannot simply depend on network density and travel data to make the decision. We studied the COVID-19 outbreak in the US in this paper, but the proposed methodologies can be applied to other countries and other epidemics. Aside from linking network density and air travel data, the use of pandemic network density can be extended to investigate the association between pandemic risk and population mobility.

Contributors

MKPS and AMYC conceptualized the study. JNLC collected and analyzed the data. AT, MKPS, ACY, and AMYC interpreted the results. ACY and AMYC drafted the manuscript. AT and MKPS finalized the manuscript. All authors read and approved the final version of the manuscript.

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Declaration of interests

We declare no competing interests.

Data sharing

All data used are publicly available, and sources are cited throughout.

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