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Comparative and quantitative analysis of COVID-19 epidemic interventions in Chinese provinces

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ABSTRACT
A mathematical model was developed to evaluate and compare the effects and intensity of the coronavirus disease 2019 prevention and control measures in Chinese provinces. The time course of the disease with government intervention was described using a dynamic model. The estimated government intervention parameters and area difference between with and without intervention were considered as the intervention intensity and effect, respectively. The model of the disease time course without government intervention predicted that by April 30, 2020, about 3.08% of the population would have been diagnosed with coronavirus disease 2019 in China. Guangdong Province averted the most cases. Comprehensive intervention measures, in which social distancing measures may have played a greater role than isolation measures, resulted in reduced infection cases. Shanghai had the highest intervention intensity. In the context of the global coronavirus disease 2019 pandemic, the prevention and control experience of some key areas in China (such as Shanghai and Guangdong) can provide references for outbreak control in many countries.

Introduction

An unknown new human coronavirus, now termed coronavirus disease 2019 (COVID-19), was identified in December 2019 in the Chinese city of Wuhan. Following the Spring Festival in China, suspected cases appeared in other regions of China and other countries, and the number of confirmed patients increased rapidly [1]. At the end of January 2020, the World Health Organization (WHO) listed this outbreak of COVID-19 as a public health emergency of international concern [2]. Although the virus was first discovered in Wuhan, the original source of the virus is still undetermined. Recent traceability studies have confirmed that the virus has appeared in some Western countries before the Wuhan outbreak [3,4]. Due to the exponential nature of the transmission, WHO declared COVID-19 a global pandemic on March 11, 2020 [5]. As of May 5, 2021, more than 150 million confirmed cases had been reported worldwide, covering almost all countries, including the United States, India, Brazil, France, Turkey, Russia, the United Kingdom, Italy, and Spain, among others [6].

Although scholars have constructed different models to evaluate the epidemiological features and the trend of COVID-19 transmission, its basic reproduction number (R0) remains uncertain. Most researchers have estimated that R0 is around 3 or even lower in China [7–9]. In past studies, owing to methodological differences (including model assumptions and parameter selections), the estimated values of

Abbreviations: COVID-19, coronavirus disease 2019; WHO, World Health Organization; R0, basic reproduction number; CDC, Chinese Center for Disease Control and Prevention; Rt, effective reproduction number; QR, healthy quick response; SARS, severe acute respiratory syndrome.

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RO have varied substantially. These variations resulted in RO being either underestimated or overestimated, which may affect the effectiveness of prevention and control strategies.

In the early outbreak period, some researchers constructed relatively simple models to explore the epidemic characteristics of the disease in China quickly [10,11]. However, with the intensification of prevention protocols and increased implementation of control measures in the country, the earlier models ceased to be completely consistent with reality. Although some scholars have constructed complex models to conduct prediction research [12-14], most of them were aimed at a single city or a few regions; some of these models are not based on real-time mobility data. Therefore, it is necessary to build a more accurate model to obtain reliable prediction results covering all 31 provinces in China.

With the unprecedented escalation of the COVID-19 pandemic, WHO warned of exponential growth momentum [15]. As the first epicenter of the outbreak, to bring the COVID-19 epidemic under control, all provinces in China made proactive and very aggressive efforts to contain it. Immediately after the lockdown of Wuhan and nearby cities in Hubei province on January 23, 2020, many provinces, including Hubei, immediately adopted strategies of strict social distancing, early detection, and isolation. Wei et al. confirmed the effect of implementing clinical diagnostic standards and investigating general symptoms, which reduced the scale and duration of the epidemic in Wuhan [12]. A study using a transmission model based on data from Wuhan, Shanghai, and Hunan provinces showed that the social distancing implemented during the outbreak alone was sufficient to control COVID-19 [16]. Pan et al. found that a series of multifaceted public health interventions was associated with improved control of the COVID-19 outbreak in Wuhan [17]. Various prevention and control measures have been implemented in different Chinese provinces; however, only a few studies have evaluated the effectiveness and intensity of prevention and control measures in all Chinese provinces.

Therefore, it is necessary to build a sophisticated model to incorporate more comprehensive variables reflecting the features of this epidemic as well as intervention measures; this would help to represent the complicated epidemic situation and intervention effects in all 31 Chinese provinces more effectively. With this objective, a mathematical model based on real-time mobility data was developed to fit the epidemic trends in various Chinese provinces and quantitatively evaluate the effects and intensity of the prevention and control measures of each province. This model can provide a valuable reference for policymakers in various countries, enabling them to choose more effective prevention and control strategies.

Methods

Data collection

In this study, the dynamic mobility data of various Chinese provinces were used to reproduce the trend of the epidemic. The migration rates between pairs of provinces and the emigration rates of individual provinces from January 1, 2020, to April 30, 2020, were collected first. The migration rate from province A to province B is the proportion of the population who migrated from A to B in one day over the total emigration population, whereas the emigration rate of province A is the proportion of the total emigration over the total population of A. These data were collected from the location-based services of the Baidu Corporation (Beijing, China). The population data of the provinces were obtained from the corresponding items in Baidu Encyclopedia, which were recorded in 2018. The Chinese Center for Disease Control and Prevention (CDC) reported the daily and cumulative numbers of newly confirmed cases, deaths, and cured individuals from January 23, 2020 to March 2, 2020; these data were collected for our study to avoid the effects of imported cases.

Model procedure

As government intervention plays a key role in disease control, a complex network of coupled populations (a metapopulation) [18] is used, in which the local disease time course is described by a dynamic model [19] with government intervention to simulate the epidemic trend in China (Net-SEAIHRQ), as shown in Fig. 1:

\[
\frac{dS_i(t)}{dt} = \left(\beta c(t) + cq(t)(1-\beta)\right)S_i(t)I_1(t) + \delta E_i(t) + \lambda S_i(t) + \Delta S_i(t) + M_{S_i}(t)
\]

\[
\frac{dE_i(t)}{dt} = \left(\beta c(t)(1-q(t))S_i(t)I_1(t) + \delta A_i(t) + q(t)E_i(t)\right) - \sigma E_i(t) + M_{E_i}(t)
\]

\[
\frac{dA_i(t)}{dt} = (1-\rho)E_i(t) - \lambda A_i(t) + M_{A_i}(t)
\]

\[
\frac{dH_i(t)}{dt} = \sigma E_i(t) - (\phi + 1 - \psi)A_i(t) + M_{H_i}(t)
\]

\[
\frac{dS_1(t)}{dt} = \left(\beta c(t)q(t)S_i(t)I_1(t) + \delta A_i(t) + q(t)E_i(t)\right) - \phi S_1(t) + M_{S_1}(t)
\]

\[
R_i(t) = N_i(t) - S_i(t) - I_1(t) - E_i(t) - A_i(t) - H_i(t) - E_2(t) - S_2(t)
\]

\[
M_{S_i}(t) = \sum_{j=1}^{n} a_j(t)p_{ijn}(t)S_i(t) - a_i(t)S_i(t)
\]

\[
M_{E_i}(t) = \sum_{j=1}^{n} a_j(t)p_{ijn}(t)E_j(t) - a_i(t)E_i(t)
\]

\[
M_{A_i}(t) = \sum_{j=1}^{n} a_j(t)p_{ijn}(t)A_i(t) - a_i(t)A_i(t)
\]

\[
M_{H_i}(t) = \sum_{j=1}^{n} a_j(t)p_{ijn}(t)H_j(t) - a_i(t)H_i(t)
\]

where \(n\) indicates the province; \(N_i(t)\) is the population of province \(n\) at time \(t\); and \(S_i(t), E_i(t), A_i(t), I_1(t), H_i(t), S_1(t), E_2(t), \text{and } R_i(t)\) correspond to the absolute numbers of susceptible individuals, exposed individuals, asymptomatic individuals, infected individuals with symptoms, hospitalized confirmed patients, quarantined susceptible individuals, quarantined exposed individuals, and removed (cured or dead) patients in province \(n\) at time \(t\), respectively. We assumed that all confirmed individuals would be admitted to hospitals (either specialist or modular hospitals), which means that the number of hospitalized confirmed patients was considered to be the number of confirmed cases in our model. \(a_i(t)\) is the emigration rate of province \(n\) at time \(t\). \(p_{tmn}(t)\) is the migration rate from province \(m\) to \(n\). \(\sigma\) is the transition rate of infected patients to confirmed patients during the incubation period, which is considered to be the reciprocal of the incubation period. \(\lambda\) is the rate at which susceptible individuals are released, which is the transition rate of the quarantined susceptible individuals to susceptible individuals and is considered to be the reciprocal of the isolation observation period. \(\beta\) and \(\rho\) are the probability of transmission per contact and proportion of infected people with symptoms, respectively. They both describe the intensity of the infection. \(\phi\), \(\psi\), and \(\lambda\) are the recovery rates of symptomatic infected individuals, asymptomatic infected individuals, and hospitalized individuals, respectively. \(\delta\) and \(\phi\) are the rates of conver-
hospitalized individuals. In addition, \( q \) and \( \nu \) are used to estimate the difference between asymptomatic and incubation period of infected individuals and symptomatic ones. All parameters are shown in Supplementary Table 1. The government intervention to reduce the contact rate and improve quarantine measures for province \( n \) was modeled as
\[
\begin{align*}
c_n(t) &= c_0 \exp\left(-\eta_n^c(t - \ell_n^c)\right) \\
q_n(t) &= q(1 - \exp(-\eta_n^q(t - \ell_n^q)))
\end{align*}
\]
where \( \ell_n^c, \eta_n^c, \) and \( \eta_n^q \) are the initial time and strength of government intervention of province \( n \). \( c_n(t) \) and \( q_n(t) \) are functions of time \( t \), which indicate the influence due to government intervention.

Model implementation

The incubation and quarantine periods were set to 5.1 and 14 days, respectively [20]. The start time for issuing a first-level public health emergency response in each province was set as \( \ell_n^c \). A retrospective study [21] revealed that the earliest confirmed case occurred on December 1, 2019. Thus, the starting time of the simulation was set to December 1, 2019, and the initial number of infections was estimated by the model.

In fact, with the continuous implementation of epidemic prevention and control, newly confirmed domestic cases on the Chinese mainland dropped to single digits in mid-March 2020. And at the end of April 2020, an initial victory in the prevention and control of the epidemic was achieved [22]. The first imported case in China occurred on March 2, 2020. Due to the continuous deterioration of overseas epidemics and the increasing of imported cases from abroad, China’s epidemic prevention work has entered a normalization stage from April 29. Prevention and control strategies have also changed to “guard against imported cases and preventing a resurgence of the outbreak at home”[22]. Whereas the Chinese government has divided the tasks of different provinces in the phase of preventing imported cases differently (some provinces assume the responsibility of the first point of entry, while some provinces are not responsible for this task), the intensity of prevention and control in this phase in each province is not considered in this study. To avoid contamination by external input of infected individuals, the data obtained until March 1, 2020 were used for model training, and the model predicted the number of cases until April 30, 2020. The remaining parameters were estimated using the least squares method with multiple population genetic algorithms.

After estimation, the \( R_0 \) for each province was calculated using the next-generation matrix method [23]:
\[
R_n(t) = \frac{\beta c_n(t)(1 - q_n(t))S_n(t)}{N_n(t)} \left( \frac{\nu}{\sigma} + \frac{(1 - \rho)\theta}{\gamma} + \frac{\rho}{\phi \delta + (1 - \phi)\eta} \right)
\]

Similarly, the reproduction number considering population migration for all provinces was calculated:
\[
\begin{align*}
C(t) &= \begin{pmatrix} c_1(t) & \cdots & 0 \\
0 & \cdots & c_{31}(t) \end{pmatrix} \\
Q(t) &= \begin{pmatrix} q_1(t) & \cdots & 0 \\
0 & \cdots & q_{31}(t) \end{pmatrix} \\
S(i) &= \begin{pmatrix} S_1(i) & \cdots & 0 \\
0 & \cdots & S_{31}(i) \end{pmatrix} \\
N(i) &= \begin{pmatrix} N_1(i) & \cdots & 0 \\
0 & \cdots & N_{31}(i) \end{pmatrix} \\
M(i) &= \begin{pmatrix} -1 & \cdots & p_{131}(t) \\
p_{311}(t) & \cdots & -1 \end{pmatrix} \\
G_1(t) &= \begin{pmatrix} \sigma & 0 & \cdots & 0 \\
0 & \cdots & \sigma \end{pmatrix}^{-1} M(t) \\
G_2(t) &= \begin{pmatrix} \sigma(1 - \rho) & 0 & \cdots & 0 \\
0 & \cdots & \sigma(1 - \rho) \end{pmatrix}^{-1} M(t) \\
G_3(t) &= \begin{pmatrix} \sigma(1 - \rho) & 0 & \cdots & 0 \\
0 & \cdots & \sigma(1 - \rho) \end{pmatrix}^{-1} G_2(t)
\end{align*}
\]
Introduction number was considered to be asymptomatic individuals. The probability of infection per contact infected in the incubation period was 1.12 times that of the infected but incubation period (calculated infection rate coefficient for patients infected and in the incubation period) was estimated to be 2.57. The disease transmission capacity of the asymptomatic infected individuals (0) was estimated to be 2.3, and the calculated infection rate coefficient for patients infected and in the incubation period (0) was 2.57. The disease transmission capacity of the infected in the incubation period was 1.12 times that of the infected but asymptomatic individuals. The probability of infection per contact within 5.2 days (0) was calculated to be 0.0487. Notably, the proportion of infections by asymptomatic individuals (0) was estimated to be 38.7%. In other words, most cases resulted from infection by asymptomatic or mild cases.

Epidemic progression in mainland China predicted using Net-SEAIHRQ model without intervention measures

According to the Net-SEAIHRQ model without intervention measures, the prediction results show that without control measures, the number of confirmed cases in China would have reached 43 million by April 30 (Fig. 4). Approximately 3.8 million people in Guangdong province were predicted to become confirmed patients, making it the province with the most confirmed patients in China. Meanwhile, Hubei province, as the province with the most actual confirmed cases, was predicted to have 1.8 million confirmed cases if the government had not taken preventive and control measures.

In this study, the actual area difference under the curve was used to measure the comprehensive effects of prevention and control measures in all provinces. In other words, the difference between the areas under the unprotected prediction epidemic curve and actual predicted curve with the integrated intervention was used to estimate the number of confirmed cases avoided. The three provinces with the largest area differences were determined to be Guangdong, Chongqing, and Henan. Among the top ten provinces with the largest regional differences, more than half of them are eastern developed regions (Table 1). It can be seen that the effects of the prevention and control measures of economically developed provinces are relatively more prominent.

Comparison of effects of different prevention and control measures

Fig. 5 shows the effects of different intervention strategies on the number of cumulative infected cases per day in China from December 1, 2019 to April 30, 2020. The prediction results of the mixed intervention measures model show that there would have been 1.5 million infected people in China, whereas that of the unprotected measures model show that there would have been 1.2 billion infected people in China. If the only measure implemented had been isolating of the infected and the close contacts of the infected, about 670 million people would have been infected. Finally, if only social distancing had been implemented, about 3.4 million people would have been infected. In summary, the prevention and control effects of the different intervention strategies are, in descending order, mixed, social distancing, isolation, and unprotected measures.

Intervention intensities of various provinces in mainland China

Table 2 reports the rankings of the provincial-level administrative regions in mainland China according to the two prevention and control intensity indicators of social distancing and isolation. After adjusting for the population densities of the provinces, the three regions with the most intense social distancing measures were determined to be Shanghai, Beijing, and Tianjin. In terms of the intensity of isolation implementation, the top three provinces were identified as Shanghai, Zhejiang, and Beijing. Whether it is social distancing measures or isolation measures, more than half of the top ten provinces in terms of intensity are in the eastern region. In other words, provinces with higher levels of economic development have relatively greater intensity of prevention and control measures.

Discussion

Although the COVID-19 epidemic in China has been brought under control, the virus is still spreading widely across other parts of the world. The results of this study show that the very proactive and aggressive containment measures that had been implemented had not been taken by all 31 provinces in China, approximately 3.08% of the Chinese population (43 million) would have been diagnosed with COVID-19 by April 30, 2020. Unlike some countries that hesitated to declare a state of emergency until the epidemic became severe for fear of possible economic interruption, many provincial governments in China chose to take the risk of detrimental economic effects to impede the rapid spread of the epidemic. In addition to the very proactive and aggressive measure of declaring the first-level emergency at a very early stage, many provinces quickly followed up by implementing all effective measures taken by the leading provinces. To the best of our knowledge, this study is the first to include an analysis of the intervention effects and intensity of COVID-19 epidemic control measures in various provinces in China based on the Net-SEAIHRQ model.

In this investigation, a more sophisticated Net-SEAIHRQ model was constructed based on real-time mobility data to fit the daily newly
Fig. 2. Distribution of confirmed COVID-19 cases and Net-SEAIHRQ model predictions. (A) Confirmed COVID-19 cases in each province in China as of April 30, 2020. (B) Net-SEAIHRQ model fitting results in the 10 provinces with the most cumulative confirmed cases of COVID-19 in reality.
Fig. 3. Effective reproduction number ($R_t$) of COVID-19 estimates in China.

Fig. 4. Prediction results of unprotected Net-SEAIHRQ model in the 10 provinces with the most cumulative confirmed cases of COVID-19 in China in reality.
diagnosed cases in various Chinese provinces; the model obtained good fitting results with actual cases. Our results demonstrate that asymptomatic or mild cases account for about 60% of all infections. Li et al. estimated that 79% of the actual documented cases in Wuhan resulted from infection by asymptomatic individuals [24]. After considering the results of several studies, Chowell suggested that asymptomatic and mild cases together account for 40–50% of all infections [25, 26]. Our study also revealed that asymptomatic individuals are more likely to cause infections than infected persons who are in the incubation period and confirmed patients with noticeable symptoms. The most probable explanation for this is that, owing to the drastic measures taken in cases of infection and the close contact tracing adopted in many provinces, once the nucleic acid test of an individual is reported to be positive or a person is identified as a close contact, the individual is quickly hospitalized or placed in designated, centralized observation buildings instead of being allowed to return home for self-isolation. This approach greatly reduces the probability of confirmed infected individuals subsequently infecting their neighbors and communities. Meanwhile, because asymptomatic infected people generally have no noticeable symptoms, they will not seek medical care or be identified for a considerably long time; thus, they will have more opportunities to spread the virus to close contacts [27]. Overall, it is imperative to screen asymptomatic patients and avoid secondary outbreaks. Notably, a city-wide nucleic acid test has been completed in Wuhan, which will help reveal the current asymptomatic infected population base.

In the initial stage of the epidemic, $R_0$ was estimated to be about 2.75, which is approximately consistent with previous research results [8, 27]. The present study also proved that the $R_0$ values of COVID-19 and severe acute respiratory syndrome (SARS) were very similar in the initial stages of these epidemics (2.75 vs. 2.9) [28]. Nevertheless, it should be noted that the $R_0$ value estimated in this study could be the result of active surveillance, centralized isolation, and strict social distancing strategies in all Chinese provinces. Tian et al. found that before the closure of Wuhan, the $R_0$ value of COVID-19 was 3.15 (95% confidence interval: 3.04–3.26) [29]. To reduce the $R_0$ to less than 1, bringing the epidemic under control, various Chinese provinces had adopted unique measures and effectively curtailed the spread of COVID-19.

The results of this study reveal that the comprehensive effect of prevention and control measures in Guangdong was the best in China. If no intervention measures had been taken, the cumulative number of confirmed cases would have reached 3.3% of the total population of Guangdong province. In general, the effective prevention and control achieved in Guangdong are attributable to three factors. First, Guangdong

| Rank | Province | Area under predicted value curve | Area under true value curve | Difference |
|------|----------|----------------------------------|-----------------------------|------------|
| 1    | Guangdong | 20,060,276                       | 24,726                      | 20,035,550 |
| 2    | Zhejiang  | 13,836,812                       | 20,850                      | 13,815,962 |
| 3    | Shanghai  | 10,506,117                       | 6315                        | 10,499,801 |
| 4    | Jiangsu   | 9,977,520                        | 10,216                      | 9,967,304  |
| 5    | Beijing   | 9,018,388                        | 7015                        | 9,011,373  |
| 6    | Hubei     | 9,819,052                        | 1,420,627                   | 8,398,425  |
| 7    | Yunnan    | 8,362,726                        | 3436                        | 8,359,290  |
| 8    | Fujian    | 8,330,145                        | 5496                        | 8,324,649  |
| 9    | Shaanxi   | 7,852,841                        | 5229                        | 7,847,212  |
| 10   | Chongqing | 7,791,348                        | 9957                        | 7,781,391  |

**Table 1** Ten Chinese provinces with the best control effects by using two evaluation methods.

**Fig. 5.** Effects of different intervention strategies on cumulative infected cases per day in China from December 1, 2019, to April 30, 2020.
Shenzhen on January 19, 2020. Four days later, Guangdong province confirmed the first case of COVID-19 in Guangdong province. However, other provinces were well prepared for outbreak areas. We can see from Table 2 that the intensity of government isolation measures in provinces with the highest number of confirmed cases, Shanghai and Guangdong, are significantly higher than those of other provinces. For example, in Shanghai, the isolation measures were implemented as early as January 22, 2020, one day before the Wuhan lockdown. The Beijing government issued a document that outlined the emergency measures as early as January 22, 2020, one day before the Wuhan lockdown. The following day, the Beijing Cultural Tourism Department issued a document to cancel all large-scale activities and prevent people from gathering and coming into contact with each other. Notably, the wide dissemination of COVID-19 knowledge played an important role in maintaining thorough public compliance to the social distancing measures implemented to contain COVID-19 [31]. Although the results of this study emphasize that isolation measures may not be as effective as social distancing measures, these measures are still effective in fighting against the epidemic, preventing 560 million Chinese from being infected with COVID-19. In this study, Shanghai, Zhejiang, and Beijing were identified as the three regions that implemented the most intense isolation measures. The Shanghai government required that the contacts found through epidemiological investigation be subjected to centralized isolation observation. Further, the Shanghai government supported prevention and control measures through emergency legislation; hence, those contacts who refuse to cooperate are required to do so by law. On February 11, 2020, healthy quick response (QR) codes were first applied in Zhejiang and then promoted nationwide. The QR codes are based on user movement over 14 days [30]. When the health QR code is red or yellow, people are required to isolate themselves until they have met the conditions for release, at which point, the health QR code is changed to green. The implementation of the health QR code not only facilitates the passage of people, but also helps the CDC track close contacts. The Beijing government also adopted centralized isolation measures for close contacts. To meet the centralized isolation needs, as of mid-February, Beijing had set up 38 designated buildings with capacities of more than 2,000 people for centralized observation and isolation of the close contacts of confirmed cases. Later, the Beijing government implemented a stricter isolation and tracking policy, expanding the definition of close contacts to those who did not take effective protective measures against close contacts within 1 m from 4 days before the symptoms of suspected or confirmed cases appeared, or 4 days before the acquisition of asymptomatic infected samples.

Several limitations of this study should be acknowledged. First, as the medical record data of infections are not publicly accessible, it was not possible to obtain information about susceptible people or a better estimate of the trend of COVID-19 [12]. Second, the model constructed in this study is very complex; hence, an interval estimate of the relevant results cannot be obtained. For the same reason, the mean square error was used as the optimized criterion rather than likelihood. Third, the influence of potential confounding factors such as population age structure, temperature, and economic level were not considered, which may affect the results of the prevention and control effect evaluation. Finally, only the intensity of social distancing and isolation measures were ranked. The evaluation of the effectiveness of other prevention and control measures, such as the ability of hospitals to treat patients, may be additionally explored in future research.

Conclusion

The proposed Net-SEAIHRQ dynamics model fit the data from the various provinces well in terms of the number of confirmed cases. We predicted that if no measures had been taken, 3.08% of the population of China would have been diagnosed with COVID-19 by the end of April 2020, and more than 95% of the people would have become infected. The simulation results from different models showed that strict social distancing is the most effective method of prevention and control, and this measure in conjunction with isolation and traffic control can effectively reduce additional COVID-19 cases before a vaccine is developed. In China, Guangdong province exhibited the best prevention and control effect, and Shanghai implemented the most intense social distancing measures and measures to isolate close contacts. In the context of the global COVID-19 pandemic, the prevention and control experiences in these key areas can provide valuable reference information for outbreak areas.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rinp.2021.104305.

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