5-18-2020

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*Mathematical Biosciences
and Engineering*

Research article

Phase-adjusted estimation of the COVID-19 outbreak in South Korea under multi-source data and adjustment measures: a modelling study

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Abstract: Based on the reported data from February 16, 2020 to March 9, 2020 in South Korea including confirmed cases, death cases and recovery cases, the control reproduction number was estimated respectively at different control measure phases using Markov chain Monte Carlo method and presented using the resulting posterior mean and 95% credible interval (C_rI). At the early phase from February 16 to February 24, we estimate the basic reproduction number R_0 of COVID-19 to be 4.79(95% C_rI $4.38 - 5.2$). The estimated control reproduction number dropped rapidly to $R_c \approx 0.32$(95% C_rI $0.19 - 0.47$) at the second phase from February 25 to March 2 because of the voluntary lockdown measures. At the third phase from March 3 to March 9, we estimate R_c to be 0.27 (95% C_rI $0.14 - 0.42$). We predict that the final size of the COVID-19 outbreak in South Korea is 9661 (95% C_rI $8660 - 11100$) and the whole epidemic will be over by late April. It is found that reducing contact rate and enhancing the testing speed will have the impact on the peak value and the peak time.

Keywords: COVID-19; mathematical modelling; the reproduction number; the final size

1. Introduction

An outbreak of atypical pneumonia was first detected and reported in Wuhan, China on December, 2019. Within weeks of its emergence, severe acute respiratory syndrome coronavirus 2 (SARS-Cov-2), was identified as the cause of these pneumonia cases. On February 11, 2020, the World Health Organization (WHO) established COVID-19 standing for Coronavirus Disease 2019 as the name of the disease caused by SARS-Cov-2. The virus subsequently spread to all provinces of China and the WHO declared the outbreak of COVID-19 a Public Health Emergency of International Concern on January 30, 2020. As of March 22, 2020, a total of 81,498 cases including 3267 deaths had been reported in Mainland China [1]. Now, the virus has spread to more than 120 countries and the WHO on March 11, 2020 declared COVID-19 a pandemic. The level of concern in Europe, Iran, USA, South Korea and Japan increased due to a surging of cases recently. South Korea had issued this infectious disease crisis alert to its highest level on February 23, 2020.

The first case in South Korea was reported on January 19, 2020 when the individual was arriving in Incheon and was quarantined at Incheon airport. The first 28 cases were confirmed till February 10, 2020 by tracing the contact persons and making the observation. In the next few days, one infection caused by unknown reason was reported every day. After February 18, 2020, the daily new cases began to rapidly increase. Up to February 24, 2020, the cumulative number of confirmed cases increased to 833 with 8 deaths from 31 cases on February 18, 2020. More than 60 percent of the 833 cases comes from Daegu City which is the original outbreak site and the remaining cases distributed the whole South Korea. Daegu and gyeongsangbuk-do where more than 80 percent of cases were concentrated, were listed as the special management areas by the South Korea government on February 25, 2020. Moreover, to mitigate the spread of the virus, the South Korea government have adopted comprehensive prevention and control measures such as postponing school start dates, scheduling different commute times, carrying out large-scale nucleic acid testing in drive-thru centers and so on. In response to the long waiting time for hospitalization caused by the rapid increase in confirmed cases, number one and number two quick-built "life treatment centers" began to accept patients with mild symptoms since March 3, 2020 [2]. It was the first time to implement the group isolation as the apartment in South Korea on March 7, 2020.

The basic reproduction number R_0 could be used to measure the transmission ability of a virus at the initial stage in the outbreak. The control reproduction number R_c reflects the transmission ability when some control measures are implemented at the transmission process. These estimations are very important for predicting the spread of the epidemic and assessing the effectiveness of control measures. Over the past month, many researchers reported the estimation of R_0 for COVID-19 and generated valuable predictions for the early phase of this outbreak. Wu *et al.* [3] estimated the basic reproduction number was 2.68 (95% C_rI $2.47 - 2.86$) and that 75815 individuals (95% C_rI $37304 - 130330$) could have been infected in Wuhan as of January 25, 2020. Based on the assumption of the mean detection window of 7.5 days, Nishiura *et al.* [4] estimated the incidence of infection in Wuhan at 20,767 infected individuals on January 29, 2020 by using Japanese passengers data on evacuation flights from January 29 to January 31, 2020. Zhao *et al.* [5] considered the unreported cases and the reporting rate in different phases and estimated R_0 at 2.56 (95% C_rI $2.49 - 2.63$). Tang *et al.* [6, 7] made the significant alert for COVID-19 by R_0 and quantified the interventions effective by the effective daily reproduction ratio. An infectious disease dynamical SEIR (Susceptible, Exposed, Infectious, and Removed) model [8] was

applied to estimate the epidemic trend in Wuhan, China. It computed the effective reproduction number at different four phases with varying intervention measures. Nishiura [9] estimated the incidence of infection with novel coronavirus (COVID-19) on the Diamond Princess by employing a backcalculation method. The work [10] studied the COVID-19 outbreak on the Diamond Princess cruise ship and obtained the median value of R_0 at 2.28 (95% C_rI 2.06 − 2.52) and the size of the cumulative cases in the following days. Few study has focused on this infection disease outbreak in South Korea. Due to the hard efforts and practical experiences in the containment measures and strategies of controlling COVID-19 prevalence, the timely surveillance and adequate nucleic acid detecting at the early phase can be supplied in Korea. Therefore, fitting the reported data in the outbreak in South Korea by the dynamical model will make a better understanding and we can predict the prevalent situation and account for the effectiveness of public health inventions and measures.

2. Materials and methods

2.1. Data Source

The Korea Centers for Disease Control and Prevention (KCDC) report the data twice daily from January 20, 2020, 9:00 and 16:00 respectively. Since March 2, 2020, KCD changed to update COVID-19 statistic data daily as of 0: 00. Here, we collected the reported data of daily infected cases as of 16:00 in South Korea from January 20 to March 9, 2020 [11]. The KCDC has conducted contact tracing activities for the first 46 confirmed cases and released the information of the tracing and mapping to public on February 19, 2020. It was found that all cases were related with travel activities or contacts with confirmed cases till mid-February. The strategies to contain the virus worked well by strictly screening travelers at the airports and tracing and quaranting the closed contracts of confirmed cases. However, a few cases with unknown infection source including case ID 29, 30, 31, 32, 38 and 46 were reported since February 16, 2020 (See Figure 1). Moreover, case ID 31 confirmed on February 18, 2020 is considered as a super-spreader. Case 31 attended services at a church twice in Daegu and traveled extensively through South Korea. Soon she began to develop some symptoms and still continued her regular routine. Since then, a dramatic spike in cases can be seen in South Korea. Therefore, we chose February 16, 2020 as the starting time in the fitting. We will fit the cumulative confirmed cases, the cumulative death cases and the cumulative recovery cases in South Korea from February 16 to March 9, 2020 in order to evaluate the effectiveness of adjusted control measures.

2.2. Model

Based on the epidemiological status of individuals and control interventions in South Korea, hospital treatment and self-isolation after an infectious individual is diagnosed are incorporated in the basic SEIR epidemic model. The total population at time t, denoted by $N(t)$, includes the following epidemiological compartments: susceptible (S), exposed (E), infectious (I), hospital treated (H) and home quarantined (Q). Susceptible population move to the latent compartment E upon the successful exposure by contacting the infection source including exposed, infectious and self-isolated population. Here, we consider that self-isolation may still be possible to infect the family members. Let β is the probability of successful disease transmission during each contact and c is the contact rate per unit time per individual. The incubation period averagely is $\frac{1}{\delta}$. The infection with symptom onset is diagnosed
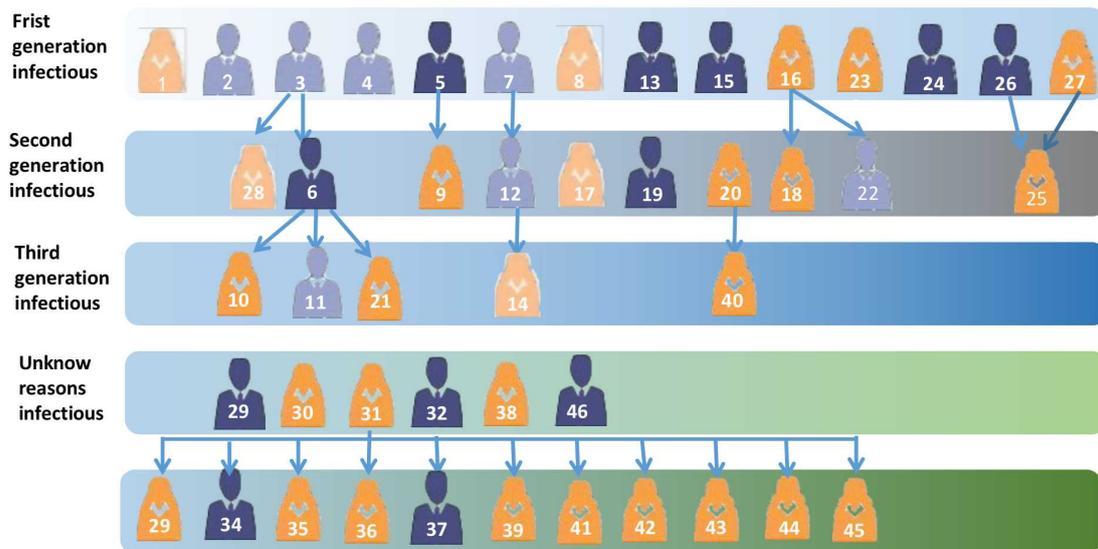
Figure 1. The transmission chain and their status for korean COVID-19 patients from case ID 1 to case ID 46. Yellow represents women and blue is men. Dark color is in the hospital and gray color is discharged.

over the period $\frac{1}{\theta}$ through Real-Time Reverse Transcription-Polymerase (RT-PCR) tests. We assume that both exposed and infectious population carry the virus and may spread it to others. Meanwhile, a proportion κ of confirmed infectious cases will be treated in hospitals and the rest will be advised under self-isolation and wait for the possible future health care. d is denoted as the disease-induced death rate. γ_h is the recovery rate under hospital treatment. $\frac{1}{\rho}$ is the median waiting time of hospitalization. $0 < \varepsilon < 1$ and $0 < \eta < 1$ are scalars for the transmission from exposed population and self-isolated population compared with that from infectious population, respectively. The transmission dynamics are governed by the following system of equations:

$$
\begin{aligned}
\frac{dS}{dt} &= -\beta c \frac{S}{N}(\varepsilon E + I + \eta Q), \\
\frac{dE}{dt} &= \beta c \frac{S}{N}(\varepsilon E + I + \eta Q) - \delta E, \\
\frac{dI}{dt} &= \delta E - \theta I, \\
\frac{dH}{dt} &= \kappa \theta I - \gamma_h H - dH + \rho Q, \\
\frac{dQ}{dt} &= (1 - \kappa)\theta I - \rho Q \\
\frac{dR}{dt} &= \gamma_h H,
\end{aligned}
\tag{2.1}
$$

Using the next generation matrix [12, 13], we obtain the expression for the basic reproduction number or the effective control reproduction number as follows:

$$R_0 = \frac{\beta c}{\theta} + \frac{\beta c \varepsilon}{\delta} + \frac{\eta \beta c (1 - k)}{\rho}.$$

2.3. Estimation of model parameters

We will estimate the basic reproduction number and the effective control reproduction number under three different phases. The first phase (from February 16, 2020 to February 24, 2020) can be regarded as the early phase of the epidemic when a few prevention and control measures were implemented. On February 25, 2020, the South Korea government began to warn the residents to take precautions and all public libraries, museum, churches, day-care centers and courts were closed in Daegu, the epicenter of the outbreak [14]. The control measures were continuously enhanced in the second phase (from February 25, 2020 to March 2, 2020). On March 3, 2020, the government stated that the detection speed of the novel coronavirus SARS-COV-2 would be greatly improved [15] and placed all government agencies on a 24-hour full alert. Meanwhile, some temporary treatment centers equipped with certain medical facilities began to accept patients with mild symptoms [16].

For the first 28 confirmed cases at the first phase, we collected the dates of entry to South Korea, symptom onset, diagnosis time (for hospitalization and/or self-isolation) and close contact numbers (See Table 1). No imputation was made for missing data. It was calculated that the average contact rate per day per person was 14.2 and the mean duration from onset-of-symptoms to diagnosis was 3.4 day. The average incubation period is assumed to be 5.2 days (95% $C_r I$ $4.1 - 7.0$) [17, 18, 19, 20] and the proportion κ as 0.56 [21] according to the new sites reports. The initial values of $H(0)$, $Q(0)$ and $R(0)$ are given based on the reported data on February 26, 2020. Other parameters and the initial values of $S(0)$, $E(0)$ and $I(0)$ are estimated (See Table 2).

At the second phase, people are encouraged to work at home and reduce the unnecessary gathering activities and so on. Therefore, we assume that the values of parameters remain the same as the first phase except the contact rate c and the disease related death rate d.

Since the third phase, more than 500 'drive-thru' coronavirus testing stations were launched in South Korea to provide free tests to people in a less crowded manner. Then the detection speed were greatly improved and the values of the remaining parameters are the same as the second phase except the mean duration from onset-of-symptom to diagnosis $1/\theta$.

We denote $Y_1(t)$ as the cumulative confirmed cases at time t, then $\frac{d}{dt}Y_1(t) = \theta I$. And we denote $Y_2(t)$ as the cumulative death cases at time t, then $\frac{d}{dt}Y_2(t) = dH$. Together with $R(t)$ as the cumulative recovery cases at time t, We regarded these three groups reported cases as three random variables following Poisson-distribution respectively, and fitted our model to real data by sampling the posterior distribution of the parameter vector. To carry out the Markov chain Monte Carlo (MCMC) procedure, we used an adaptive Metropolis-Hastings (M-H) algorithm. The algorithm was run for 20,000 iterations and we discarded with the first 10,000 iterations as a burn-in period. The median and confidence interval of each estimated parameter are listed in the Table 2.

Table 1. Summary of movement paths of COVID-19 confirmed patients in South Korea [22].

| Case ID	Date of entry	Symptom onset	Confirmed time	Contact number
#1	1/19/2020 (fever)	—	1/20/2020	45 (1 day)
#2	1/22/2020 (fever)	—	1/24/2020	75 (2 days)
#3	1/20/2020 (asymptomatic)	some symptomatic, 1/25/2020	1/26/2020	98 (6 days)
#4	1/20/2020	fever, muscle soreness, 1/25/2020	1/27/2020	172 (6 days)
#5	1/24/2020 (asymptomatic)	some symptomatic, 1/29/2020	1/30/2020	35 (6 days)
#6	—	—-	1/30/2020	25 (5 days)
#7	1/23/2020 (asymptomatic)	cough, 1/26/2020	1/30/2020	21 (6 days)
#8	1/23/2020 (asymptomatic)	fever, cough 1/27/2020	1/31/2020	76 (6 days)
#9	—	—	1/31/2020	2 (1 day)
#10	—	—	1/31/2020	91 (6 days)
#11	—	—	1/31/2020	0
#12	—	some symptomatic, 1/30/2020	2/1/2020	666 (6 days)
#13	1/31/2020 (fever)	—	2/1/2020	0
#14	—	some symptomatic, 1/30/2020	2/2/2020	0
#15	1/20/2020 (asymptomatic)	some symptomatic, 2/1/2020	2/2/2020	12 (6 days)
#16	1/19/2020 (asymptomatic)	aversion to cold, fever 1/25/2020	2/4/2020	45 (6 days)
#17	1/24/2020 (asymptomatic)	fever 1/26/2020	2/5/2020	290 (6 days)
#18	—	—	2/5/2020	4 (6 days)
#19	1/24/2020 (asymptomatic)	—	2/5/2020	54 (6 days)
#20	—	some symptomatic, 2/5/2020	2/5/2020	0
#21	—	some symptomatic, 2/3/2020	2/5/2020	7 (6 days)
#22	—	some symptomatic, 2/6/2020	2/6/2020	1 (6 days)
#23	1/23/2020 (asymptomatic)	some symptomatic, 2/6/2020	2/6/2020	23 (6 days)
#24	—	sore throat 2/6/2020	2/6/2020	0
#25	—	—	2/9/2020	11 (6 days)
#26	1/31/2020 (asymptomatic)	2/8/2020	2/9/2020	0
#27	1/31/2020 (asymptomatic)	some symptomatic, 2/5/2020	2/9/2020	37 (6 days)
#28	—	—	2/10/2020	1 (6 days)

Table 2. Parameters estimated values and interpretation at the three different transmission stages.

| Stage	parameter	Estimation mean value	Interpretation and Dimension	std	Source
I	β	0.054895	Probability of transmission per contact (dimensionless)	0.0053708	MCMC
I	ε	0.53146	Infectious ability of the latent (dimensionless)	0.07827	MCMC
I	η	0.013321	Infectious ability of the home quarantine (dimensionless)	0.07827	MCMC
I	γ_h	0.00021393	Recovery rate of infected individuals by the hospital treatment (day^{-1})	0.00081283	MCMC
I	d	0.0066965	Disease induced death rate (day^{-1})	0.002261	MCMC
I	ρ	0.54158	Hospitalization proportion of diagnosed infected individuals (dimensionless)	0.15755	MCMC
I	S(0)	$2.0314 * 10^6$	Initial susceptible population (humans)	$5.284 * 10^5$	MCMC
I	E(0)	78.854	Initial latent population (humans)	34.944	MCMC
I	I(0)	58.898	Initial infectious population (humans)	32.68	MCMC
II	c	0.95887	contact rate (per person per day)	0.23925	MCMC
II	d	$1.0959 * 10^{-3}$	Disease induced death rate (day^{-1})	$2.838 * 10^{-4}$	MCMC
III	$\frac{1}{\theta}$	2.3	Mean period from onset to diagnosis (day)	0.08611	MCMC

3. Results

By using the proposed model to fit the reported numbers of confirmed, death and recovered cases (see Figures 2 and 3), we estimate the basic reproduction number $R_0 \approx 4.79$ (95% C$_r$I $4.38 - 5.2$) at the early phase and the control reproduction number $R_c \approx 0.32$ (95% C$_r$I $0.19 - 0.47$) and $R_c \approx 0.27$ (95% C$_r$I $0.14 - 0.42$) respectively at the second and third phase with the implementation of effective countermeasures. Moreover, we can also see that simulated number of daily confirmed cases fits the reported data well and the data from March 10, 2020 to March 17, 2020 are used to verity the model (see Figure 4). Meanwhile, the decline of the reproduction number is very fast at the second phase. This indicates that the prevention awareness and the cooperation degree of public in South Korean were both high and control measures were working when special management areas were set up. It was very effective that the increasing number of temporary medical treatment centers were used to isolate patients to avoid further spread. The South Korea government launched the extensive nucleic acid detection at the epidemic areas and published the movement information of diagnosed patients,

which make the great efforts in the rapid containment. At the third phase, the South Korea government announced that the whole country enter the "war" against COVID-19 and the detection speed will be significantly improved. It is known that the final size of the epidemic outbreak depends on the current control measure. Therefore, it is predicted that the estimated value of the final size is 9661 (95% C_rI 8660 − 11100) with keeping the control measures at the third phase. Moreover, we predict that the whole epidemic will be over by late April (see Figures 2 and 4).
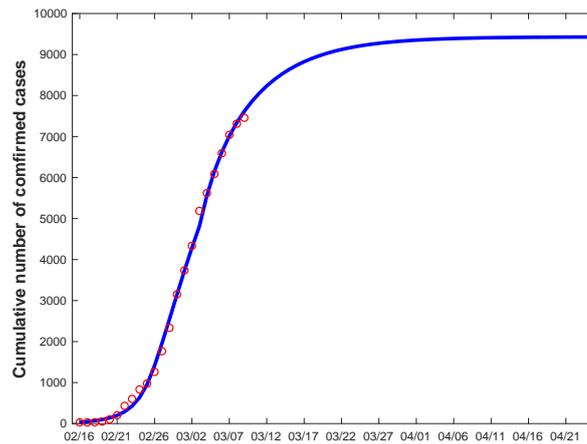
Figure 2. Estimation of the cumulative confirmed cases and the end date of the outbreak are shown.
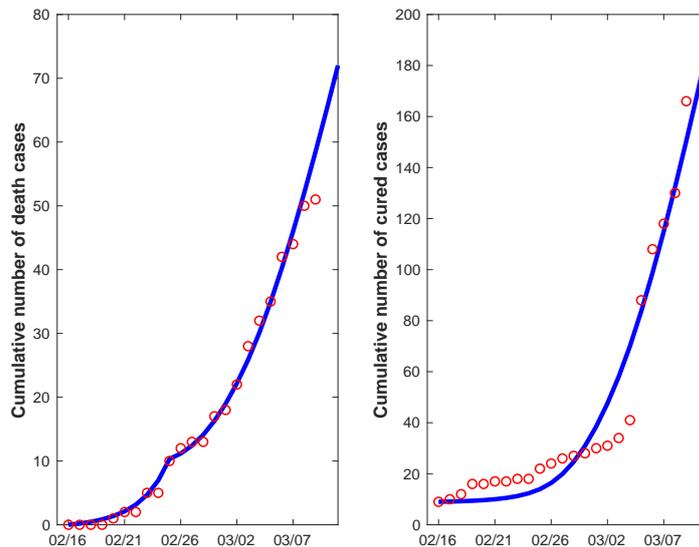
Figure 3. Estimation of the cumulative death cases and cured cases are shown respectively. Red circles represent the observed data points and the blue solid curve shows the medium value based on 10,000 simulations by our model.
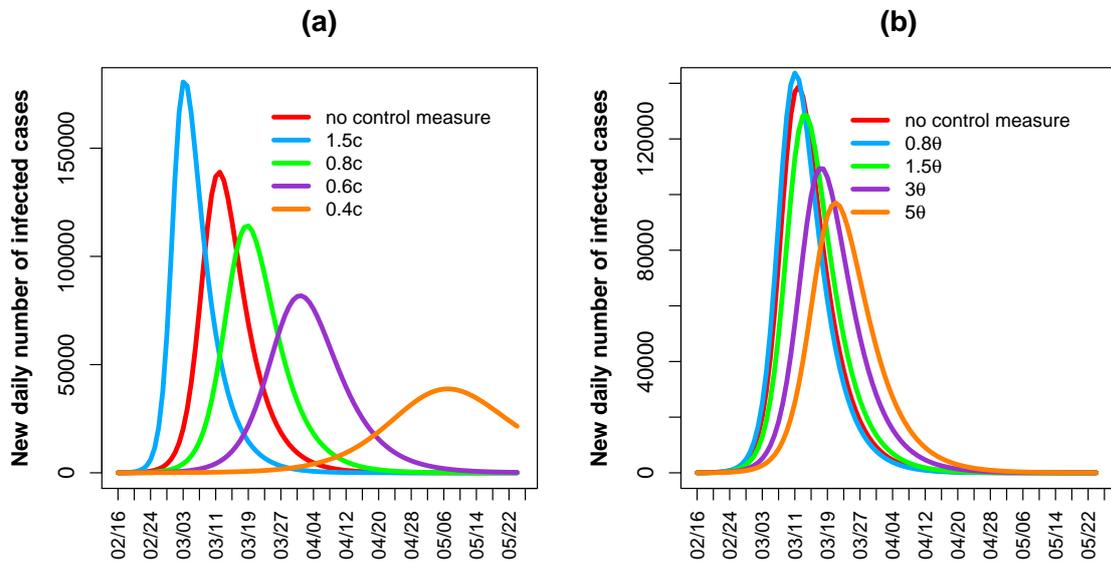
We plot the new daily infected cases with varying contact ratio c and the test ratio θ to examine the possible impact of enhanced interventions on COVID-19 infection (see Figure 5). By the sensitive analysis (see Figure 5a,b), it is found that reducing contact ratio and enhancing the testing speed not only decrease the peak value and but also delay the peak time. Moreover, compared with the diagnosed speed from 4.3 days (0.8θ) to 0.7 day (5θ), the decrease of the contact ratio from (21.4) ($1.5c$) to 5.7 ($0.4c$) per day per person will has a quick effect on containing COVID-19. It illustrates that reducing the aggregation and staying home are very important and effective. If everyone could try his or her best staying home, the spread will may be contained even if the shortage of the testing kits. It can be explained that why the spread of COVID-19 in the Europe especially in the Italy is so bad. Further, we study the impact on the peak value of new daily infected cases by combining the two parameters pair (see Figure 6). It is explained that the outbreak of COVID-19 in South Korea could be contained rapid by the incorporate control measures of the increase of detection speed, the habit of wearing a mask and reducing the aggregation.
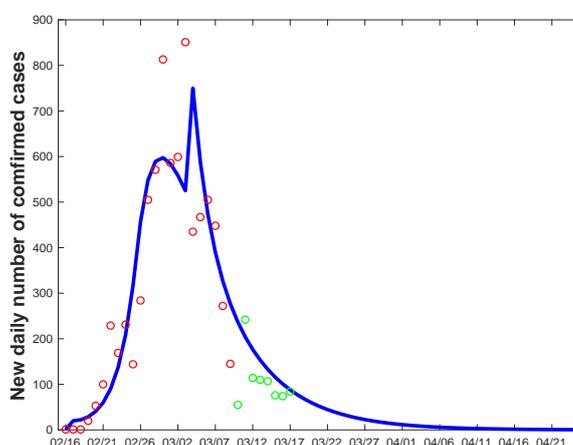

Figure 4. The good match of newly daily number of confirmed cases is shown. The red circles represent the daily reported data from February 16, 2020 to March 9, 2020 and the green circles represent the daily reported data from March 10, 2020 to March 17, 2020.

4. Conclusions

The study presents the spread and control situation of COVID-19 in South Korea by formulating mathematical modelling, estimating the basic reproduction numbers and evaluating the effectiveness and strength of control measures. According to the implementation time of control measures issued by the government, we divide the transmission process from February 16, 2020 to March 9, 2020 to three different transmission stages. We find that the decline of the control production number is rapid at the second stage. If keeping the current testing efforts and control measures, we predict that the final size of this outbreak in South Korea is 9661 (95% C_rI $8660 - 11100$) and the whole epidemic will be over by the middle of April. It is noticeable that the duration from onset-of-symptoms to diagnosis is very short worldwide. This aggressive testing capacity allowed South Korea to rapidly identify cases

Figure 5. Sensitivity analysis with respect to the contact ratio c and the test rate θ on the new daily infected cases.
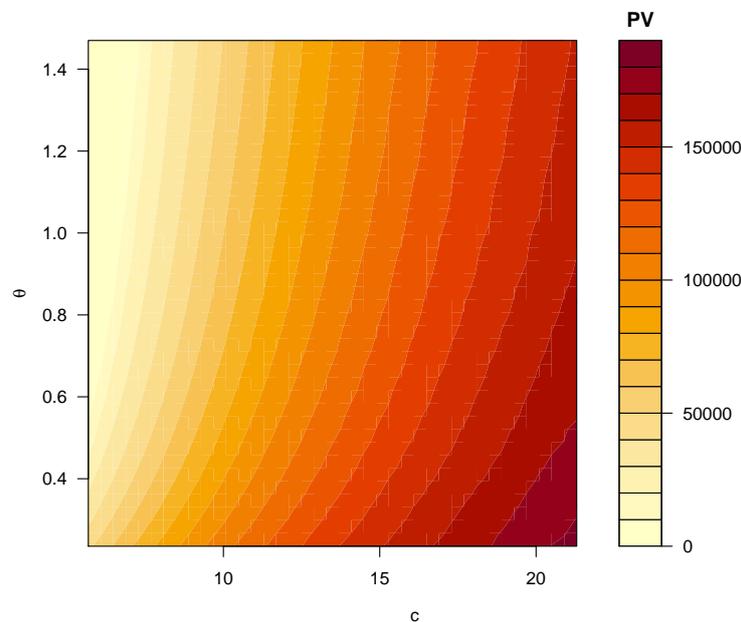
Figure 6. The contour plot of the peak value of new daily infected cases in terms of the parameters θ and c.

and then isolate them quickly and this also allowed the government to effectively control the virus spread without shutting everything down. Actually, there have been 10,765 cases of COVID-19 as of April 30, 2020 in South Korea and it was the first time since February that no locally infected cases have occurred. The signs of a slowdown were observed clearly. The final size of 10,765 stays in our prediction interval 95% C_rI (8660, 11100).

One limitation in our study is that the impact of importation is not considered. As a result of this limitation, our estimation of the end of the outbreak which was in late April is too optimistic since the South Korea is now under the pressure of the importation cases from countries who just experienced the peak or are still stay in the peak of outbreak such as Europe and the United States.

Acknowledgments

Conflict of interest

The authors declare no conflicts of interest.

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