Coronavirus disease 2019 (COVID-19) infectious trend simulation in Malaysia: a mathematical epidemiologic modelling study

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Summary

Background Since the coronavirus disease 2019 (COVID-19) outbreak appeared in the city of Wuhan, mainland China on Dec 31, 2019, the geographical spread of the epidemic was swift. Malaysia is one of the countries that were hit substantially by the outbreak, particularly in the second wave of the outbreak. We aim to simulate the infectious trend of COVID-19 in order to understand the severity of the disease and to simulate the infectious trajectory to determine the approximate number of days required for the trend to decline.

Methods We used data on the number of confirmed positive infectious cases (as reported by Ministry of Health, Malaysia (MOH)) from Jan 25, 2020 to March 31, 2020 in order to infer the severity of the COVID-19 infectious trend in Malaysia. We simulated the infectious count for the same duration to assess the predictive capability of the Susceptible-Infectious-Recovered (SIR) model. Furthermore, we used the same model to project the simulation trajectory of confirmed positive infectious cases for 80 days from the beginning of the outbreak and extended the trajectory for another 30 days to obtain an overall picture of the severity of the disease in Malaysia. We also utilised the transmission rate β to predict the cumulative number of infectious individuals.

Findings By using the SIR model, we obtained the simulated infectious cases count which was not far off from the actual count. The simulated trend was able to mimic the actual count and also capture the spikes in the actual approximately. The infectious trajectory simulation for 80 days and the extended trajectory for 110 days depicts that the inclining trend has reached its peak and has ended, and will start declining towards late April, 2020. Furthermore, our predicted cumulative number of infectious individuals tallies with the preparations undertaken by the MOH.

Interpretation The simulation provides an indication of the severity of COVID-19 disease in Malaysia, suggesting a peak of infectiousness in mid-March, 2020 and a probable decline in late April, 2020. Overall, our findings indicate that outbreak control measures such as the Movement Control Order (MCO), social distancing and increased hygienic awareness is needed to control the transmission of the outbreak in Malaysia.

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Introduction

The first incidence of coronavirus disease 2019 (COVID-19) was reported in mainland China, in the city of Wuhan on Dec 31, 2019. Ever since then, the geographical spread of the epidemic was swift and beyond control, hence turning it into a pandemic.[1] Beginning on Feb 26, 2020, the number of COVID-19 cases increased rapidly worldwide when compared to inside China. Massive substantial outbreaks was observed in the USA, Italy and Iran. COVID-19 is caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2)[2] that has resulted in more than 130 000 deaths within a short span of time. The death toll of COVID-19 is extremely greater than that of the other infectious diseases caused by viruses such as SARS, MERS, Ebola, and H1N1.[3] At the onset of COVID-19, patients usually show symptoms connected to viral pneumonia, usually fever, cough, sore throat myalgia and fatigue.[4–9] The incubation period of COVID-19 is generally between two to 14 days or longer and usually takes five days as the average.[10,11] The virus can spread from an individual to another through respiratory droplets and close contact.[12]

The first incidence in Malaysia was reported on Jan 25, 2020 through three cases of imported COVID-19 involving three tourists from China who had entered Malaysia via Johor from Singapore on Jan 23, 2020. The first wave of the outbreak commenced on the first incidence day until Feb 16, 2020. During these 23 days period, only 22 confirmed cases were recorded with eight recovered patients and zero deaths, with minimal outbreak control measures exercised. Moreover, there were no new cases recorded for the following ten days. However, on Feb 27, 2020 new incidence involving two cases marked the beginning of the second wave of the outbreak in Malaysia. The first 18 days of the second wave did not see tremendous increase in the number of new cases, however, on March 15, 2020, the numbers had a sudden rise up to 190 individuals from only 35 on the previous day. This alarming rate was due to the identification of large clusters of susceptible individuals that were in contact with infectious individual(s). Following that, the first death incidence involving two cases occurred on March 17, 2020. The sudden hike and drastic spread of the outbreak changed the Malaysian context of the outbreak from being in-control to perilous state and triggered the implementation of the Movement Control Order (MCO) on March 18, 2020.[13] Since the first rise on March 15, 2020, the inclining trend of new cases each day continued with an average of 150 cases per day and was hit with a major spike of 235 cases on March 26, 2020. On top of that, the number of deaths started spiralling upwards, with more than 60% of deaths were patients over the age of 60 years which included those with underlying conditions such as hypertension and diabetes (as of March 31, 2020), in line with the findings from Guan and colleagues'[7] clinical progress study. The Malaysian scenario of COVID-19 outbreak from Jan 25, 2020 to Mar 31, 2020 can be visualised as in figure 1.

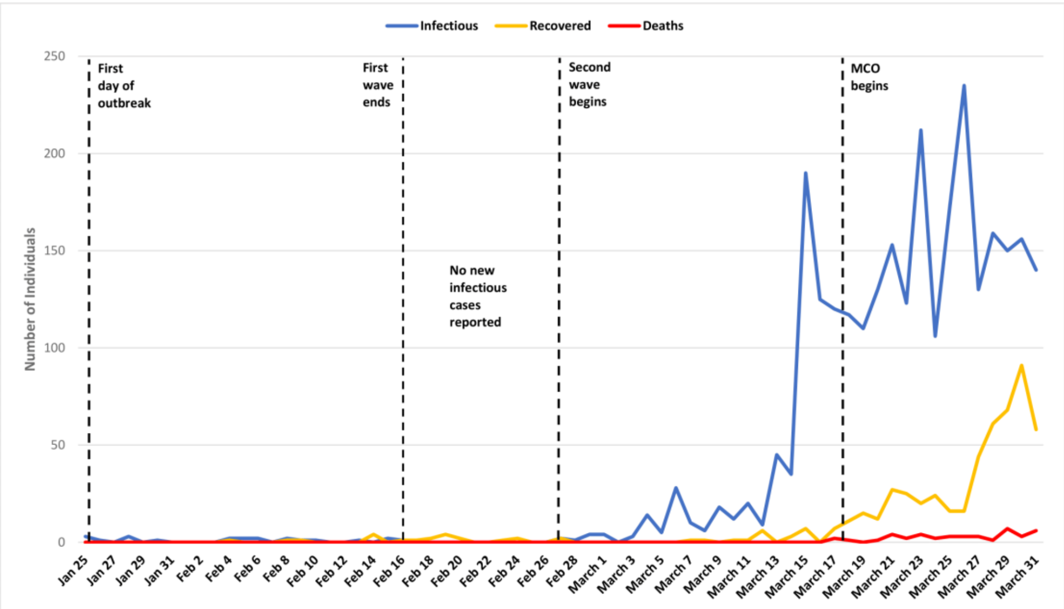

***Figure 1*: The Malaysian Scenario of COVID-19 Outbreak**

The visualisation of first 67 days of COVID-19 outbreak in Malaysia with the four major timelines marked with dotted black line. The infectious count is represented by blue line, the recovered count is represented by yellow line, and the deaths count is represented by red line.

In such a perturbing situation, assessing the infectious trend of COVID-19 in Malaysia is crucial to measure the pandemic's severity, as evidenced by the enormous growth from three cases to 2766 cases within only 67 days (March 31, 2020). Estimation of infectious count over time is able to provide a better understanding of the current epidemiological situation in Malaysia and can provide insights into the measurable effect of undertaken outbreak control measures.[14] Analysis providing such estimations enables predictions of potential future growth[15], can assist in risk estimation of regional countries[16], and planning of alternative interventions or increasing the intensity of existing interventions.[17]

Nevertheless, performing such analyses, especially in real time is often difficult due to constraints such as delay in symptom appearance resulting from the incubation period and delay in confirmation of positive cases resulting from limitations in testing and detection capacity.[14,18] Mathematical modelling of infectious diseases can help to overcome the constraints caused by the delays and uncertainty.[19] The most common modelling approach to simulate the probable outbreak trajectory and severity of an infectious disease outbreak is the Susceptible-Infectious-Recovered (SIR) model.[20] As anticipated, several studies have widely applied the SIR model[21,22] and its extensions such as the Susceptible-Exposed-Infectious-Recovered (SEIR) model[23–27] and the Susceptible-Exposed-Infectious-Hospitalised-Recovered (SEIHR)[28] to the current COVID-19 outbreak at global and national levels.

Using the SIR model, we simulated the infectious trend of COVID-19 in Malaysia to estimate the COVID-19 transmission pattern for a period of 67 days. The simulation is used to obtain an overall picture of COVID-19's potential severity in Malaysia.

Research in context
Evidence before this study

We searched Google Scholar, medRxiv, arXiv for peer-reviewed articles, preprints, and research reports on the modelling of coronavirus disease 2019 (COVID-19) severity using the search terms "COVID-19 modelling", "epidemic model COVID-19", "mathematical modelling COVID-19", "SIR COVID-19" and "SEIR COVID-19" up to March 30, 2020. No language restrictions were applied. We identified 12 papers that were relevant in the context of mathematical modelling for COVID-19 that can be applied to the Malaysian scenario. Most of the papers focused on the outbreak at the global level, in Hubei, China, China in general, South Korea, Italy, and Iran. We also found several estimates of the transmission rates, recovery rates and the basic reproductive numbers used in these papers. Until now, there has been scarce information in understanding the changing severity and transmission dynamics of COVID-19 in the South East Asia region, particularly Malaysia which holds the highest number of cases at the time of writing.

Added value of this study

In the absence of a complete study for Malaysia or the South East Asia region, we inferred the severity of COVID-19 infectiousness in Malaysia by simulating the infectious count against the actual count. We used the same model to project the simulation trajectory into the future (up to 110 days since day zero of the outbreak) to estimate the approximate number of days for the inclining trend and sudden spikes to decline. Furthermore, we predicted the cumulative number of infectious individuals in order to assess the preparations undertaken by MOH. That is, whether MOH has prepared the minimal number of beds or not.

Implications of all the available evidence

We show that the severity dynamics of COVID-19 in Malaysia is rapidly changing and should be closely monitored. Our findings suggest that outbreak control measures such as stricter enforcement of the Movement Control Order, social distancing, and increased hygienic awareness is needed in order to control the local transmission of the outbreak.

Methods

Data Sources and collection

In this modelling study, we extracted the daily number of confirmed positive (infectious) cases from the official daily statistics of COVID-19 provided on the MOH web portal.[29] The extracted records were then collated as time-series data, which begins from day zero of the COVID-19 outbreak in Malaysia (Jan 25, 2020). In order to avoid any possibility of biasness in using a single data source, we validated our figures with Kini News Lab COVID-19 tracker[30], a local website that provides real time data and information on COVID-19. These data are collected through daily press conference statements by the Director General of Health, Malaysia, where patients' data are not identifiable and remain anonymous. Hence, ethical approval is not required.

Infectious trend simulation of COVID-19 in Malaysia

In the modelling procedure, we divided the population into three compartments, as follows: susceptible $S(t)$ (number of not yet infectious and disease free individuals at time t), infectious $I(t)$ (number of confirmed or isolated individuals at time t), and recovered $R(t)$ (no longer infectious individuals at time t). We used the standard SIR epidemic model (figure 2) to simulate the infectious severity of COVID-19 in Malaysia beginning from the first day of the outbreak. This model is widely used as a first approach to analyse virus spreading and is reasonably predictive for infectious diseases which are transmitted from human to human, and where recovery confers lasting resistance, such as measles, mumps and rubella.[20]

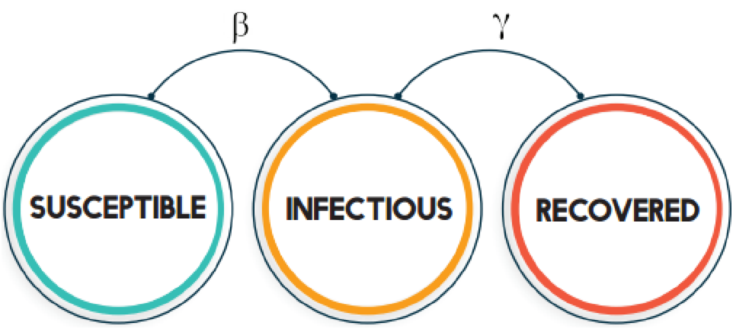

***Figure 2*: SIR State Diagram**

Individuals move from susceptible compartment to infectious compartment at the rate of β and from infectious compartment to recovered compartment at the rate of γ.

The standard SIR model assumes no births or deaths i.e. a fixed population, $N = S(t) + I(t) + R(t)$. The primary components of this model are the parameters β: transmission rate which controls the rate of spread and γ: recovery rate. If the average duration of recovery is denoted D, then the recovery rate is given by $\gamma = 1/D$, since an individual experiences one recovery in D days. Apart from these parameters, another important measure in epidemiology is the basic reproductive number R_0, which estimates the speed at which a disease is capable of spreading in a specific population.[31] The variable R_0 also indicates the number of secondary infections stemming directly from the first case in a susceptible population. When $R_0 > 1$, one infected individual will on average infect > 1 person in total. When $R_0 = 1$, we are right at the threshold between an epidemic and not. Finally, when $R_0 < 1$, one infected individual will on average infect < 1 person in total. Thus, it is the target to have mechanisms to achieve $R_0 < 1$. As disclosed by Datuk Seri Dr. Noor Hisham Abdullah, Director General of Health, Malaysia on 10 April 2020, Malaysia is approaching $R_0 = 1$.[32] This significant improvement is due to among others – the Movement Control Order (MCO), better social distancing etiquettes and hygienic practices.

The dynamics of the COVID-19 transmission can be described using the following nonlinear ordinary differential equations (ODEs) as shown below:

$$\frac{dS}{dt} = -\frac{\beta SI}{N},$$

$$\frac{dI}{dt} = \frac{\beta SI}{N} - \gamma I,$$

$$\frac{dR}{dt} = \gamma I.$$

The differential equations were numerically solved with R software environment (version 3.6.3), with Runge–Kutta (RK4) method via the package deSolve (version 1.28).[33] Data and code are available online.

Role of the funding source

The funder of the study had no role in the study design, data collection, data analysis, data interpretation, or writing of the report. The corresponding authors had full access to all the data in the study, final responsibility for the decision to submit for publication and have acquired permission from Director General of Health, Malaysia to submit these findings for publication.

Results

Actual and Simulated Current Infectious Trend

The SIR model is initialised (at time $t = 0$) with the initial conditions $S(0) = S_0 = 999$ (99.9% from total population), and $I(0) = I_0 = 1$ (0.1% from total population). We obtained the basic reproductive number R_0 for this study using the average R_0 = 2·44 estimated using stochastic methods in two previous studies[23,27]. It is consistent with the range estimated by WHO[11], and Ying and colleagues.[34] The average number of days of recovery is assumed to be $D = 11$ days based on the first recovered case in Malaysia. It follows that the recovery rate, $\gamma = 1/11$ = 0·09. Next, using $R_0 = \beta/\gamma$, [31] we derive the value of the transmission rate, β = 2·44(0·09) = 0·22. Finally, with the values of S_0, I_0, and R_0, the differential equations were solved to obtain the values of each compartments at each time point (days) beginning from day zero (25 January 2020) to day 67 (31 March 2020).

It can be seen that in the initial stage (day zero to day 15, figure 3), the simulated counts were approximately close to actual counts. However, after day 20, the simulation had an upwards trend with the peak value of 224 infectious individuals on day 56 (21 March 2020). The simulation trend started declining after day 58. On the other hand, the actual infectious counts only started increasing drastically after day 50 and there were three major spikes between days 50 and 61. The actual peak value was 235 infectious individuals on day 61 (26 March 2020).

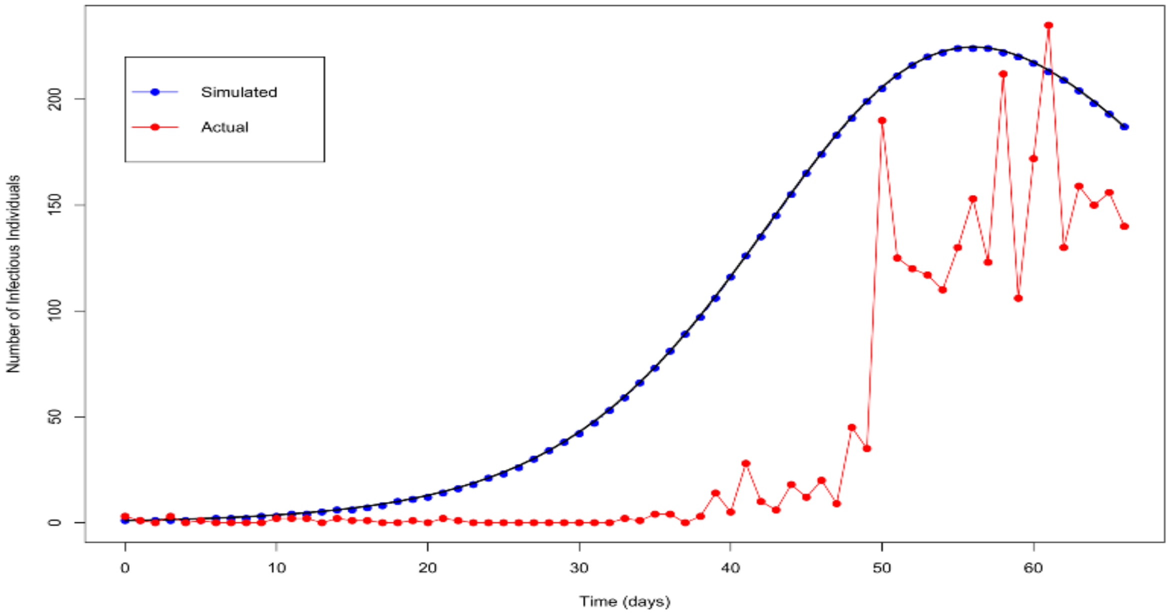

***Figure 3*: Actual versus Simulated Infectious Trend**
The actual infectious trend is represented in red dots, while the simulated infectious trend is represented in blue dots for the duration of 67 days.

The standard SIR model was able to approximately mimic the actual trend and predict the actual spikes. The discrepancy in SIR simulation between day 20 to day 50 is due to the nature of the actual counts (discrete values) when there is a sudden spike in the number of confirmed cases. Note that, the simulated peak was also approximately close to that of the actual peak. All three simulated compartments of the SIR model for the same period of time are shown in figure 4. The simulated susceptible trend declines after day 30 and further down after day 60. Whereas, the simulated recovered trend inclines after day 30 while the infectious trend steadily approaching downward trend.

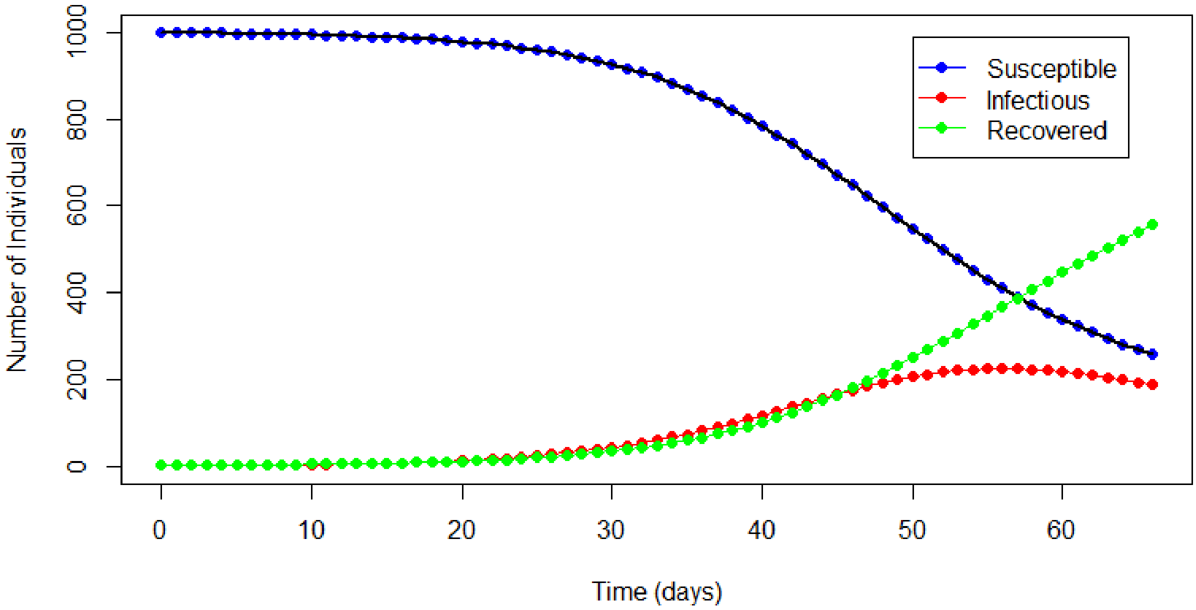

***Figure 4*: Simulated SIR Compartments**
The blue dots represent the simulated number of susceptible individuals, the red dots represent the simulated number of infectious individuals, and the yellow dots represent the simulated number of recovered individuals in the period of 67 days.

Trajectory Projection Simulation of COVID-19 in Malaysia

The predictive capability of the SIR model in the previous section is fairly good and thus, we used the same initial conditions and parameters' values to simulate the trajectory projection of COVID-19 in Malaysia. Two trajectories were produced: 80 days form day zero (until April 13, 2020) and 110 days from day zero (until May 13, 2020). Number of days for the trajectories were chosen arbitrarily to determine the approximate number of days needed for the infectious trend to completely decline since the first day of COVID-19's establishment in Malaysia.

It can be observed from figure 5 that the simulated maximum count is 224 infectious individuals in a day. Thereafter, the simulated figures dropped to below 200 infectious individuals in a day and further to below 110 infectious individuals at the end of the trajectory on April 13, 2020. For the second trajectory (figure 6), which is the extended trajectory of 30 days from the previous one, the infectious count trend declines steadily by exhibiting a downward trend from day 80 (April 13, 2020) and reaches the lowest point with less than 20 cases in a day on May 13, 2020, which indicates that the severity of COVID-19 in Malaysia may reduce by mid-May, 2020. Actual infectious count reported on April 13, 2020 was 134 new infectious individuals. In between April 14 until April 23, 2020, actual data showed a downward trend. The actual infectious counts reported were 170, 85, 110, 69, 54, 84, 36, 57, 50 and 71 new infectious individuals respectively within that time period. Except for the spike on April 14, 2020, the preceding counts maintained below the generated SIR curve. As such, evidence from actual data on infectious individuals has a strong correlation to the fact that our SIR curve is based on $\beta = 0{\cdot}22$. This implies a strong assumption that infection from an infectious individual to a susceptible individual in Malaysia is at a conservative rate. That is, at the high end, an infectious individual in

Malaysia will transmit the disease to a susceptible individual every four days, while at the low end in five days.

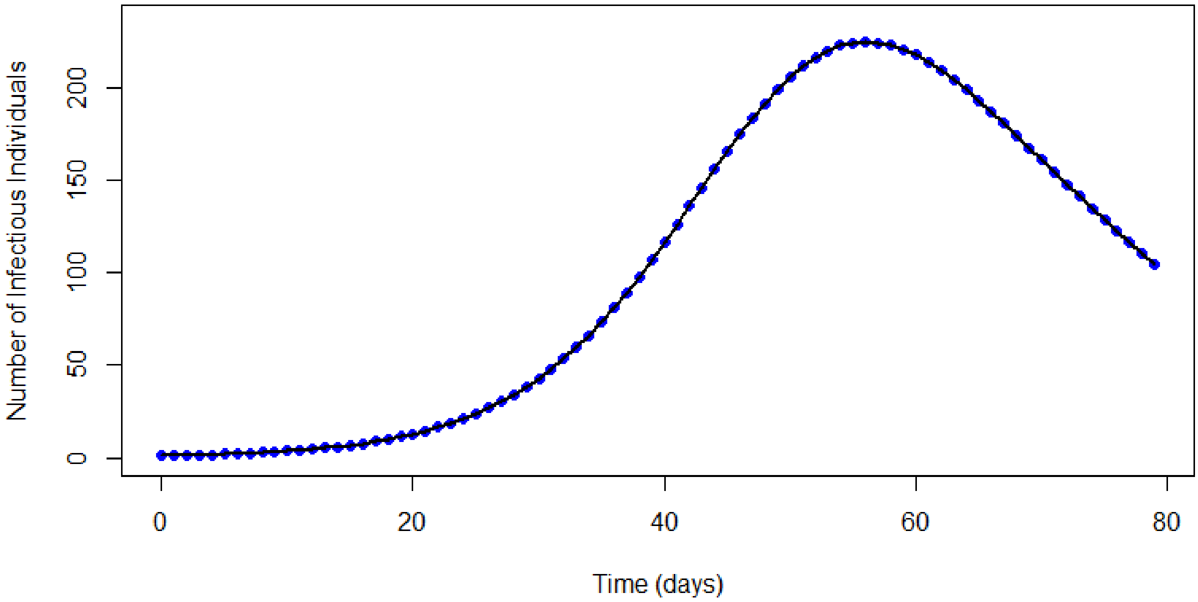

***Figure 5*: Simulated Projection of 80 Days Trajectory**
The blue dots represent the simulated projection of 80 days trajectory for the number of infectious individuals (from Jan 25, 2020 to April 13, 2020).

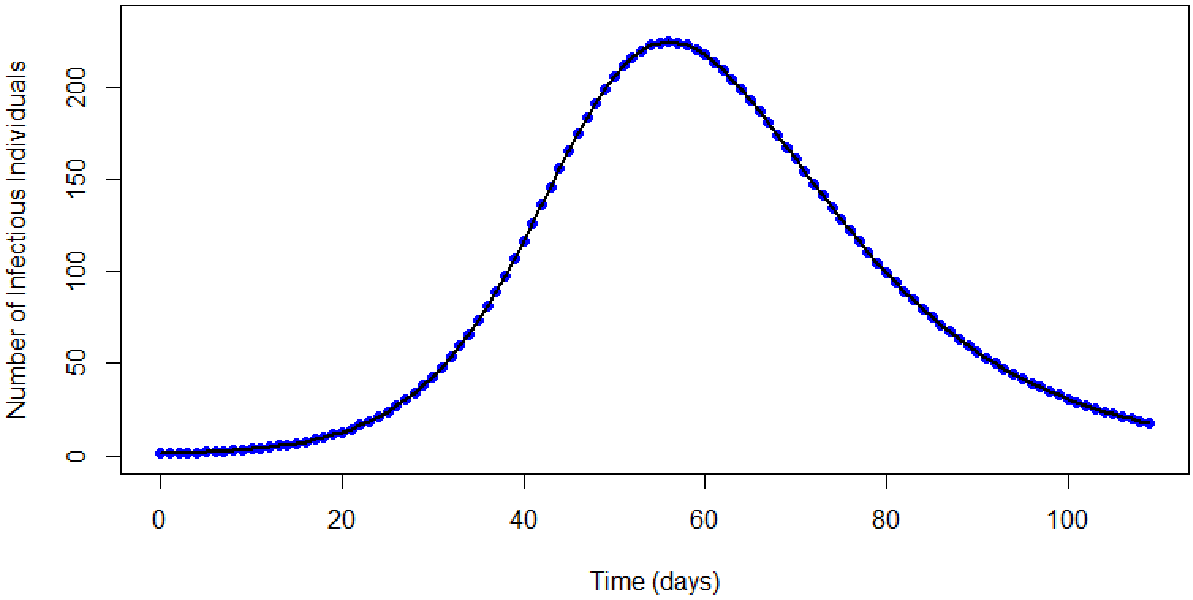

***Figure 6*: Simulated Projection of 110 Days Trajectory**
The blue dots represent the simulated projection of 110 days trajectory for the number of infectious individuals (from Jan 25, 2020 to May 13, 2020).

Discussion

Based on the SIR model's simulation, we extend our discussion to predict cumulative positive infectious cases of COVID-19 in Malaysia. This discussion is subject to further analysis, since it is not conclusive in nature. However, we would like to highlight at this point of our argument that discussions provided here are based on definitions within the literature. We will base our discussion on $\beta = 0{\cdot}22$ which implies a one-to-one transmission after four days. This assumption is conservative.

We hypothesise that after an individual becomes infected, thus becoming an infectious individual, he will only display symptom(s) after 14 days in order to be confirmed positive with the COVID-19 disease and will be hospitalised thereafter. As such, after being hospitalised he will not be able to be in contact with other susceptible individuals. We also hypothesise that during the 14 days period, an infectious individual will be able to spread the disease to another individual in a four days interval.

We assume that first three infectious individuals in Malaysia (confirmed on Jan 25, 2020) were still at large within society at that point in time. With a four days transmission rate, the next three individuals to be infectious would be on Jan 29, 2020 and the next six individuals to be infectious would be on Feb 2, 2020. On Feb 8, 2020, the first cohort of three individuals would display symptoms and be hospitalised. On Feb 12 2020, the second cohort consisting of three individuals to be infectious on Jan 29, 2020 would display symptoms and be hospitalised. On Feb 16 2020, the third cohort consisting of six individuals to be infectious on Feb 2, 2020 will show symptoms and will be hospitalised. Prior to anybody from the first to the third cohort to display symptoms and hospitalised, the fourth cohort of twelve individuals to be infectious will occur on Feb 6, 2020. This cycle repeats itself ad infinitum until certain measures are able to halt the process. Figure 7(a)–7(d) depicts this process.

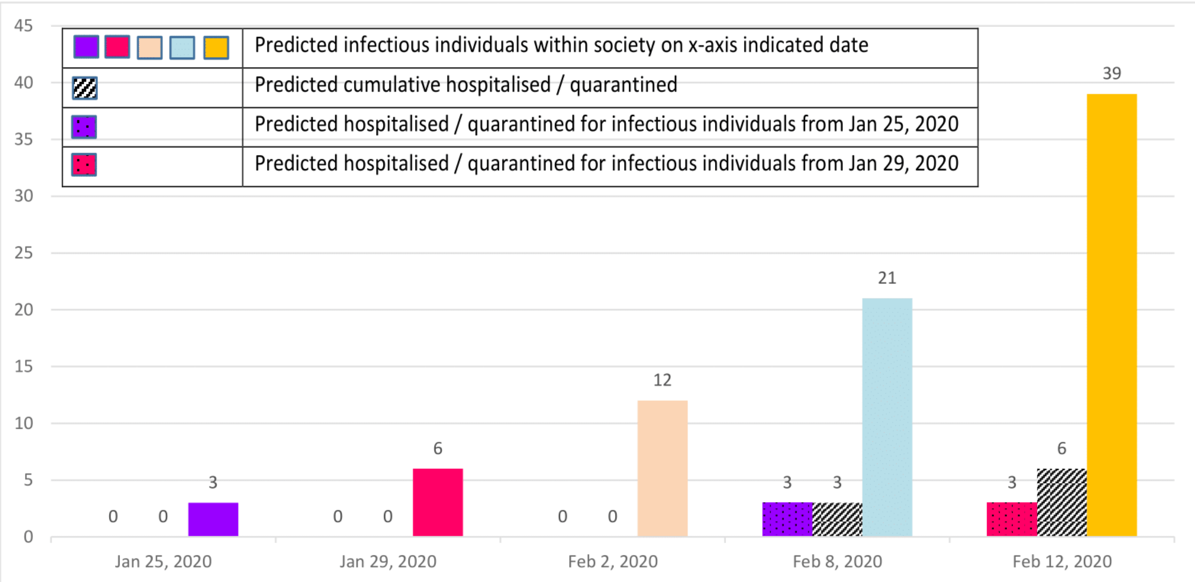

***Figure 7(a)*: Predicted Cumulative between Jan 25, 2020 and Feb 12, 2020**
A prediction based on transmission rate $\beta = 0{\cdot}22$, which translates into a four-day infection interval between Jan 25, 2020 and Feb 12, 2020. The assumption is that the total number of infectious individuals reduces is due to hospitalisation after being diagnosed as an infectious individual after a 14-day incubation period.

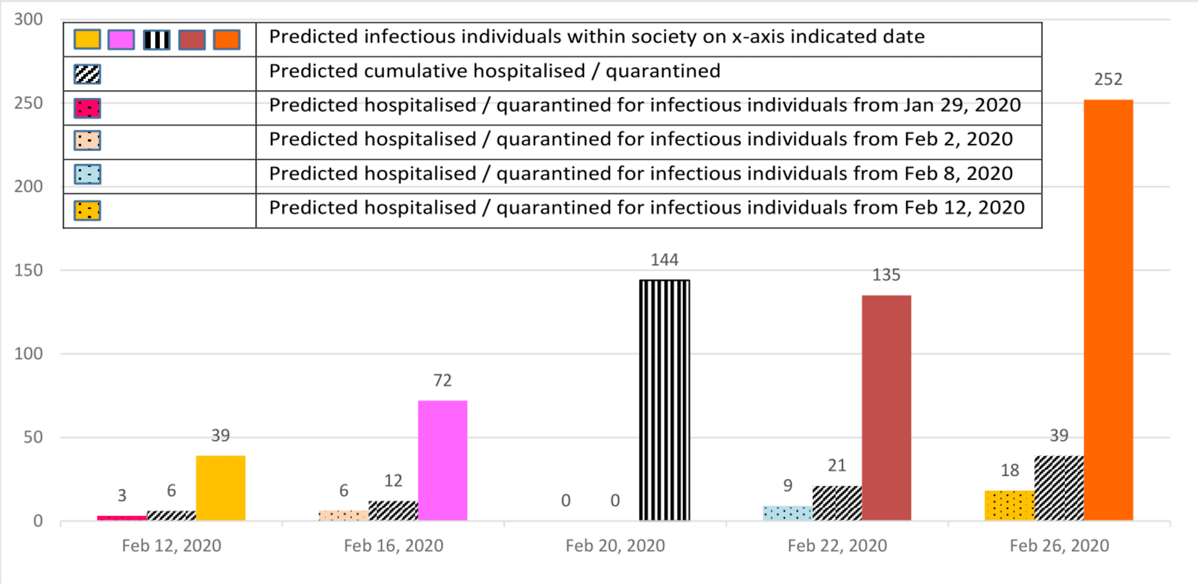

***Figure 7(b)*: Predicted Cumulative between Feb 12, 2020 and Feb 26, 2020**

A prediction based on transmission rate $\beta = 0{\cdot}22$, which translates into a four-day infection interval between Feb 12, 2020 and Feb 26, 2020. The assumption is that the total number of infectious individuals reduces is due to hospitalisation after being diagnosed as an infectious individual after a 14-day incubation period.

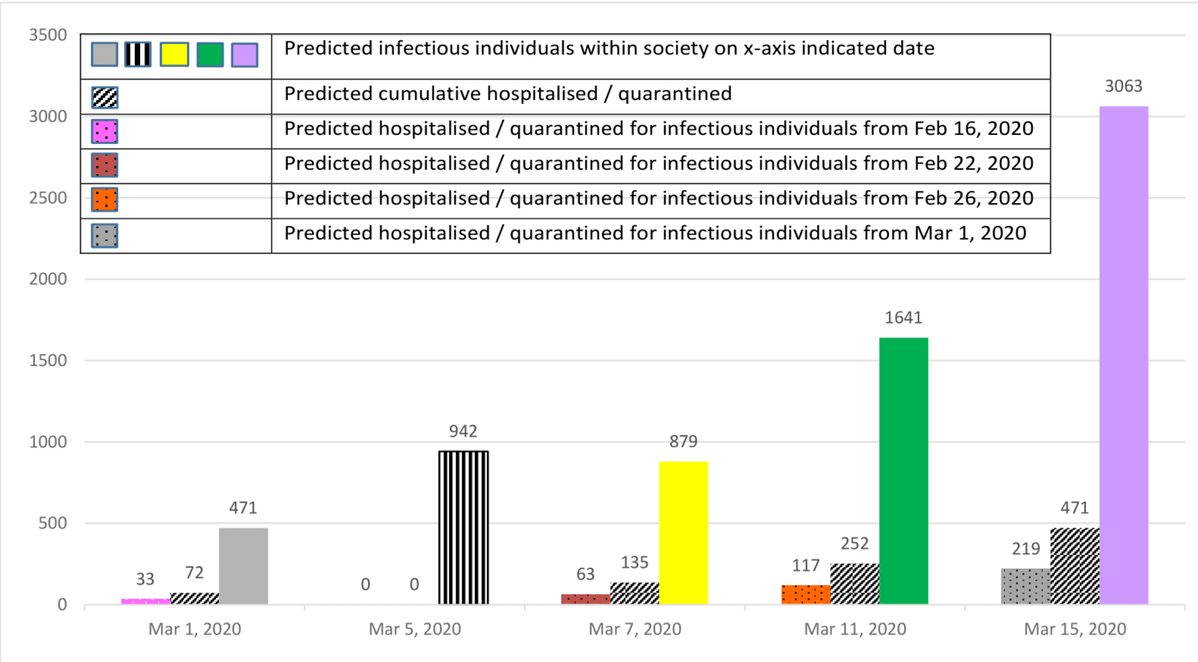

***Figure 7(c)*: Predicted Cumulative between March 1, 2020 and March 15, 2020**

A prediction based on transmission rate $\beta = 0{\cdot}22$, which translates into a four-day infection interval between March 1, 2020 and March 15, 2020. The assumption is that the total number of infectious individuals reduces is due to hospitalisation after being diagnosed as an infectious individual after a 14-day incubation period

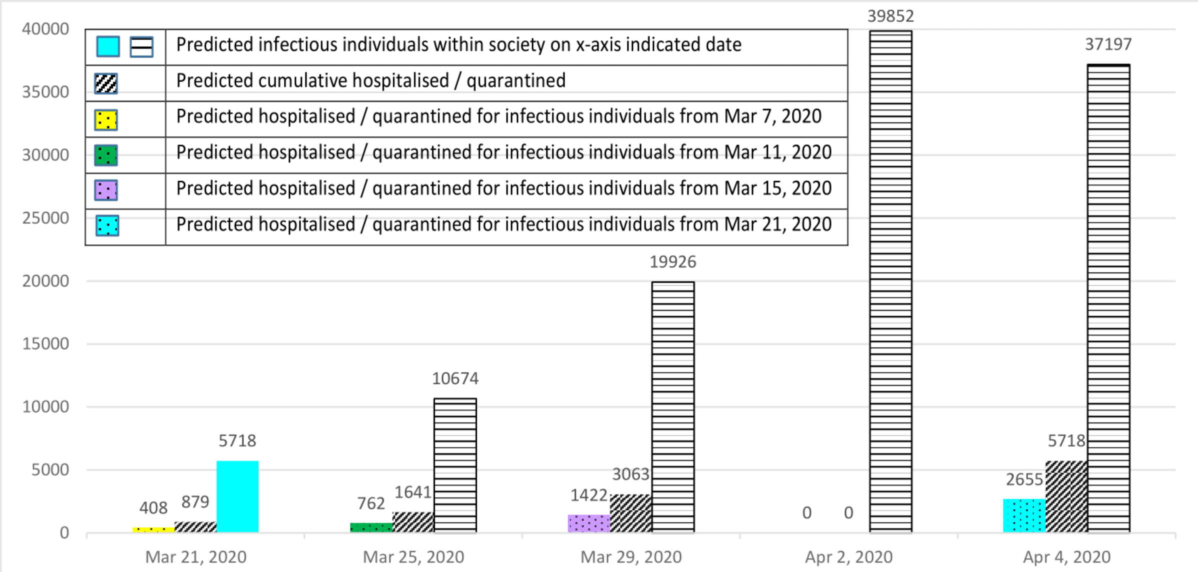

***Figure 7(d)*: Predicted Cumulative between March 21, 2020 and April 4, 2020**
A prediction based on transmission rate $\beta = 0{\cdot}22$, which translates into a four-day infection interval between March 21, 2020 and April 4, 2020. The assumption is that the total number of infectious individuals reduces is due to hospitalisation after being diagnosed as an infectious individual after a 14-day incubation period

Remark: The colour code in figure 7(a)–7(d) is used to identify the 14 day period of each infectious cohort beginning from the first day the cohort becomes infectious. For example, in figure 7(a) the colour purple-blue for the first cohort of infectious individuals on Jan 25, 2020: it is predicted that there are three infectious individuals within the society, where three of them will show symptoms and be hospitalised after a 14 day period on Feb 8, 2020. Another example in figure 7(c) and 7(d), is the colour yellow for the tenth cohort of the infectious individuals on March 7, 2020: it is predicted that there will be 879 infectious individuals within society, where 408 of them would display symptoms and be hospitalised after a 14 days period on March 21, 2020.

We note here that the actual cumulative positive cases (where we assume they are hospitalised and not in contact with other susceptible individuals) reported on March 29, 2020 is 2470 individuals. Meanwhile, the predicted cumulative number of infectious individuals to be hospitalised on March 29, 2020 is 3063. Furthermore, we have predicted that there are around 19 926 infectious individuals still roaming around in society on March 29, 2020.

Although the prediction depicted in figure 7(a)–7(d) is of exponential growth of infectious individuals, we also take note of the following:

i. The above ‘avalanche’ effect is under the assumption that no remedial action has been taken to halt interaction (except for hospitalising the infectious ones – which translates into no longer being in contact with susceptible individuals).
ii. The above ‘avalanche’ effect is under the assumption that the best fit SIR curve upon the actual infectious count (discrete data) produces the transmission rate, $\beta = 0{\cdot}22$, that is translated into the idea of one infectious individual will transmit the disease to another individual within a four day interval.

iii. On March 29, 2020, the MOH made an official announcement on the preparation of around 19 200 new beds.[35] This is a near coincidence to our prediction of 19 926 infectious individuals still roaming around within society on March 29, 2020.

The following figures present an account of our predicted values when compared to actual values reported by the MOH Malaysia on a daily basis. In both the figures below (Figure 8 and 9), the simulated cumulative is based on figure 7(a)–7(d).

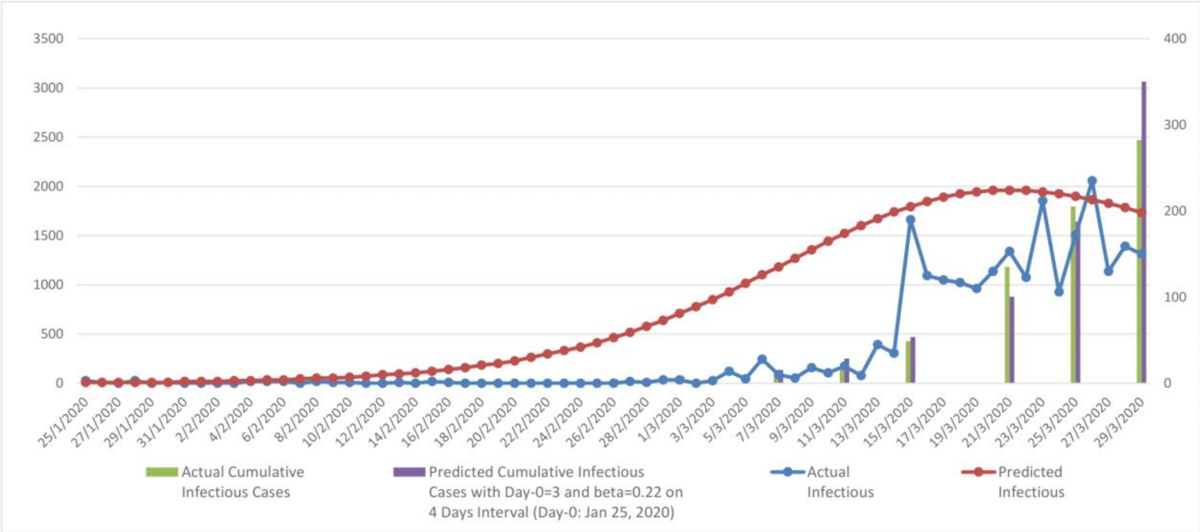

***Figure 8*: Actual versus Predicted Cases (Jan 25 to Mar 31, 2020)**
The red dots represent the predicted cumulative infectious cases, and the blue dots represent the actual cumulative infectious cases. The predicted cumulative infectious cases with I_0= 3 on 4 days interval are shown in blue bars, while the actual cumulative infectious cases are shown in orange bars.

***Figure 9*: Actual versus Predicted Cases (Mar 1 to Mar 31, 2020)**
The red dots represent the predicted cumulative infectious cases, and the blue dots represent the actual cumulative infectious cases. The data points of the actual infectious cases from Mar 15, 2020 to Mar 31, 2020 are provided on the plot to depict how close the predictions are. The predicted cumulative infectious cases with I_0= 3 on 4 days interval are shown in blue bars, while the actual cumulative infectious cases are shown in orange bars.

Table 1 summarises figure 8 and 9. One is able to observe from table 1 that the SIR model produces predicted daily values that are not far off from the actual daily values. As such, the SIR transmission rate, $\beta = 0{\cdot}22$, which corresponds to a hypothesised scenario whereby an individual will infect another individual within a four days interval, should not be taken lightly. Furthermore, a one-to-one transmission on an interval of four days can be seen to be rather conservative. Nevertheless, as shown in figure 7(a)–7(d), even at this rate, the exponential growth rate is visible.

	March 15, 2020	March 21, 2020	March 25, 2020	March 29, 2020
Actual Cumulative Infectious Cases	428	1183	1796	2470
Predicted Cumulative Infectious Cases	471	879	1641	3063
Difference	+43	-304	-155	+593
Actual Infectious Cases	190	153	172	150
Predicted Infectious Cases	205	224	217	198
Difference	+15	+71	+45	+48

***Table 1*: Difference between Actual and Predicted Cases on Selected Days**
Four days in the period from March 15, 2020 to March 31, 2020 were randomly selected to illustrate the difference between actual cumulative infectious, predicted cumulative infectious, actual infectious, and predicted infectious cases.

Although the SIR model is a numerical simulation, the numbers do provide us a high possible scenario in which the COVID-19 infectious cases can surge to. This gives us an overall picture of the infectious severity of COVID-19 in Malaysia. As COVID-19 is still an infectious pandemic with some unclear properties, accurate SIR predictions can only be obtained once the outbreak has been successfully contained.[13] To this end, these trajectories could serve as a dependable means for the Malaysian government, businesses and citizens to plan and mitigate for such spike in infectious cases. This study is believed to serve as one of the initial efforts for in-depth research on questions that revolve around this global pandemic within the Malaysian context. Our study is also a collective effort towards flattening the COVID-19 infectious curve in Malaysia and stopping the spread as per interventions set out by the government, namely the MCO. Finally, we note that this early or preliminary study is part of an ongoing wider research as more intensive studies regarding COVID-19 can be performed. An obvious future research direction for this study is to extend the current SIR model to SEIR model by including the Exposed (E) compartment in the modelling procedure.

Contributors

MRKA, KG, IK, and NMS conceived the study with inputs from ISCI and MBA. MRKA, KG, IK, ISCI, NMS and JA led the analysis of Malaysian COVID-19 data with input from MBA, NHAR and NSMD. MRKA coordinated management of the team, including the data collation and processing, research direction, interpreting of results and conceived the idea of predicting the cumulative number of infectious individuals based on the SIR transmission rate in order to gauge MOH preparations. KG developed the code for the SIR model. KG, IK, MBA and JA undertook the task of aligning the research direction with existing literature so as to not contradict existing definitions and understanding of the SIR model. Furthermore, ISCI and NMS enlightened the team with existing MOH procedures with regards to analysing national data sets prior to making it public. NSMD ensured that all presented data were reader friendly whilst retaining the intended direction. MRKA produced the first draft of the manuscript. All authors contributed to the final draft.

Declaration of interests

MRKA, KG, IK, ISCI, MBA, JA, NHAR and NSMD reports utilising resources provided by the Institute for Mathematical Research, Universiti Putra Malaysia. NAS reports resources provided by the Institute for Medical Research, Ministry of Health, Malaysia. All authors declare no competing interests.

Data sharing

All data and code used in this study are available on the dedicated COVID-19 website hosted by the Institute for Mathematical Research, Universiti Putra Malaysia.

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