Analysis of the second wave of COVID-19 in India based on SEIR model

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India is under a grave threat from the second wave of COVID-19 pandemic. The situation is rather gloomy as the number of infected individuals/active cases is increasing alarmingly compared to the first peak. Indian government/state governments are implementing various control measures such as lock-downs, setting up new hospitals, and putting travel restrictions at various stages to lighten the virus spread from the initial outbreak of the pandemic. Recently, we have studied the SEIR dynamic modelling of the epidemic evolution of COVID-19 in India (CURRENT SCIENCE, Vol. 120, pp. 1342 (2021)) with the help of appropriate parameters quantifying the various governmental actions and the intensity of individual reactions. Our analysis had predicted the scenario of the first wave quite well. In this present article, we extend our analysis to estimate the number of infected individuals in the ongoing second wave of COVID-19 in India with the help of the above SEIR model. Our findings show that the people's individual effort is the most important factor to control the pandemic in the present situation as well as in the future. We also indicate the possibility for a third wave.

In recent times, mathematical models and epidemiological modelling have proved to be helpful during the Corona-virus pandemic by offering snapshots of specific patterns such as virus spread, identifying the number of infected individuals, upcoming consequences and so on [1–5]. In order to track the transmission of the virus, one has to essentially rely on the available data and make simplified assumptions to reduce the complexity of the problem. Furthermore, one has to keep oneself up to date with all the data and observations in order to develop the models that are as close to reality as possible. This would also help in the evaluation of various scenarios, and for providing information for proper support for health care decisions.

Recently, we have studied the commonly used susceptible-exposed-infectious-removed (SEIR) model [3, 4] to account for new uncertainties, and in particular the number of infected individuals in India which were estimated during the initial lock-down and unlock periods, starting from March, 25, 2020 to October, 31, 2020 and further up to December 27, 2020, with the help of the initial rate of COVID-19 transmission by considering the initially infected people in the country [6, 7]. The prediction of the infected individuals from our model has agreed with the actual data of daily rate of infected individuals fairly well [6, 7]. In this study, we divided the common population into four compartments - susceptible, exposed, infectious and removed (which include both the cases of recovered and death numbers) with the help of appropriate differential equations to relate the parameters of the model to the population based on the initial framework of He *et al* which was proposed as a basic model that explained the 1918 influenza [8, 9]. Further, the specific aim of the proposed model was to capture the effects of the individual actions/responses (which may include personal hygiene, healthy habits, avoiding crowded places, wearing masks, washing hands frequently), in addition to the governmental action.

In this brief note, we further consider the variability in transmission rate through the values of individual action rate and governmental action strength from an all over India basis as well as in the various individual states (particularly Tamilnadu, Maharashtra, Kerala, and Karnataka), starting from Dec 2020. In particular, we examine the number of infected individuals due to the occurrence of the second wave of COVID -19, and predict the possible peaks as well as the possibility of the onset of a third wave.

The suggested SEIR model has been formulated as follows [3, 4, 6, 8, 9]:

$$\dot{S} = -\beta(t)\frac{SI}{N}, \tag{1a}$$

$$\dot{E} = \beta(t)\frac{SI}{N} - \sigma\ E, \tag{1b}$$

$$\dot{I} = \sigma E - \gamma I, \tag{1c}$$

$$\dot{R} = \gamma_R I, \tag{1d}$$

$$\dot{D} = d\gamma I - \lambda D, \tag{1e}$$

$$\dot{C} = \sigma E, \tag{1f}$$

In this model (1), S is the susceptible population, E is the exposed population, I is the currently infected population (excluding the recovered and death cases) and R is the population removed which includes both the cases of recovered and death numbers. Besides, the total population also contains two more classes: D is a public perception of risk with respect to serious cases and deaths, and C is the number of cumulative cases (both reported and not reported incidents) [3]. The following parameters were also considered in the governing equations: γ is the mean infectious period, γ_R is the delayed removal period, which denotes the relation between removed population and the infected ones, σ is the mean latent period, while d denotes the proportion of severe cases and λ is the mean duration of public reaction [3, 4, 9].

In Eq.(1), $\beta(t)$ denotes the transmission rate function which incorporates the impact of governmental action $(1-\alpha)$, and the individual action, which is denoted by the function $\left(1-\frac{D}{N}\right)^k$ [3, 9]. Here, the parameter k defines the intensity of individual reaction, which is measured on a scale of 0 to 10^5 with a normal value of 1117.3 obtained from previous and recent epidemic and pandemic studies [3, 8]. These values should be incorporated into the different values of the transmission rate which is defined as

$$\beta(t) = \beta_0(1-\alpha)\left(1-\frac{D}{N}\right)^k. \tag{2}$$

The value of β_0 is derived by assuming that the basic reproduction number is $R_0 = \frac{\beta_0}{\gamma}$, which measures the average number of new infections generated by each infected person.

TABLE I. Model parameters for Eqs. (1) and (2)

Parameter	Description	value/remarks/reference
N_0	Initial number of population	India/particular state population [10]
S_0	Initial number of susceptible population	$0.9N_0$ (constant)
E_0	Exposed persons for each infected person	$20I_0$[11]
I_0	Initial state of infected persons	3 (India)/appropriate value for specific state taken from [10
α	Government action strength	varied in each lock-down/unlock period
k	intensity of individual reaction	1117.3 [3, 9]
σ^{-1}	Mean latent period	3 (days)
γ^{-1}	Mean infectious period	5 (days)
d	Proportion of severe cases	0.2
λ^{-1}	Mean duration of public reaction	11.2 (days)

In the present study, the daily COVID-19 active cases from the whole of India as well as the individual states, namely Tamilnadu, Maharashtra, Kerala and Karnataka, for the time period 27 December 2020 to 10 May 2021 are considered. Daily active cases are collected from the data available in [11]. The parameters which are presented in Table I are employed for simulations of population N_0 and the initial number of infected individuals (I_0 varies for each state and the whole of India) relative to the initial outbreak in specific locations. The parameters α and k are only needed to be adjusted for each specific period, which have become important for the estimation of the number of infected individuals. Therefore, in the following, the rate of infection based on the transmission rate (2) is evaluated using the system of Eqs.(1) for all the above cases.

Now, we study the number of infected individuals in the whole of India by varying the strength of the individual reaction k in various intervals, with fixed value of governmental action strength $\alpha = 0.12$ as shown in Fig.1. For low values of k, it is observed that the time for the occurrence of peak of the infected individuals is delayed, that is the number of infected cases would continue to rise till May 21 (4.5 million cases, Label I in the figure) and then would start to decrease (black curve). And it may lead to the COVID-19 third wave shortly around the first week of July 2021 if the public response further decreases. However, if the strength of the public response is increased with adequate governmental

TABLE II. Variations (minimum and maximum range) of the effective reproduction number at time (R_t) in the specified time line

Region	Jan 01,21-Feb 28,21	March 01,2021-April 30,2021
India	0.9-1.2	1.49-2.2
Tamilnadu	0.9-1.26	1.07-1.8
Kerala	1.09 - 1.22	1.2-1.9
Maharashtra	1.17-1.26	1.26 - 2.01
Karnataka	1.0 - 1.28	1.26 - 2.25

action (that is the public response increases to a sufficiently higher degree) the number of infected cases would only rise till May 16th (3.8 million cases, Label II) and then would start to decrease to very low values (blue curve). Similar analysis is also carried out for four specific states of India using the initial population of each state, and the initial number of infected individuals in the specific states (data again taken from [10] and [11]). Fig. 2 shows the number of infected individuals from our model (1) in comparison with the actual data. It clearly demonstrates the occurrence of the large number of infected individuals/active cases during the second wave of COVID-19 and it mainly depends upon the individual people's reaction with adequate governmental action. Further, we also mention that the large number of infected individuals occur in some specific states like Maharashtra, Karnataka, Kerala which is mainly due to the time dependent transmission rate $\beta(t)$ in Eq.(2), and it is commensurate with the reproduction number at time t ($R_t = \frac{\beta(t)}{\gamma}$). We also present the variations of the minimum and maximum ranges of effective reproduction number for the individual affected states along with the whole of India in the specified time-line in the table II.

In summary, up to May, 13 2021, the total number of COVID-19 cases and active cases in India are 2,37,03,665 and 37,10,525, respectively. The second wave of COVID-19 in India is a potential threat to the country because of its rapid spread. Our mathematical analysis of SEIR model appears to be an effective tool to predict the time span and to investigate epidemic evolution in India.

Our projection of the different trajectories of the pandemic, based on different scenarios (decreasing the parameter k can change the dynamics of COVID-19 outbreak in active cases)

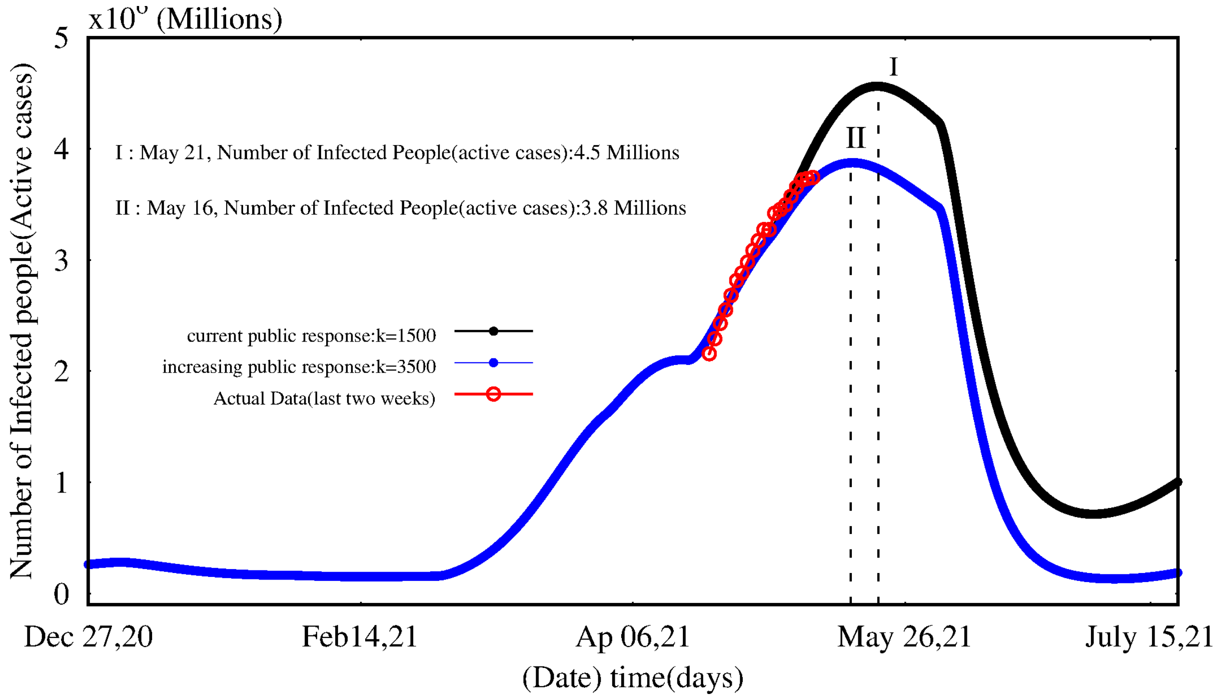

FIG. 1. Numerical simulation of the currently infected people (after removing the number of recovered people on a particular day). The curves represent the numerical simulation of the number of infected individuals (active cases) from Dec 27,2020 to July 15,2021 with respect to the values of government action strength and intensity of the individual reaction in the SEIR mathematical model. Data available between Dec. 2020 to April 2021 are taken for fitting the parameters. The red curve with circles corresponds to that the actual number of infected individuals in India during the last two weeks. The vertical black dotted lines along with label I and II denote the predicted maximum number infected individuals (active cases) on May 21 and May 16, respectively.

and estimation of the effective reproduction number suggests that at present the second wave of COVID-19 is much more infectious than the first wave. Therefore, we find that the individual actions/responses which may include personal hygiene, healthy habits, avoiding crowded places, wearing masks, washing hands frequently, etc. are equally or perhaps even more important than the government actions such as lockdown. The simple acts of not going out unnecessarily and keeping social distance can reduce the transmission of the virus. We also note that a third wave can emerge if individual action rates are reduced and it may start emerging as early as the first week of July if sufficient care is not taken up by the general public.

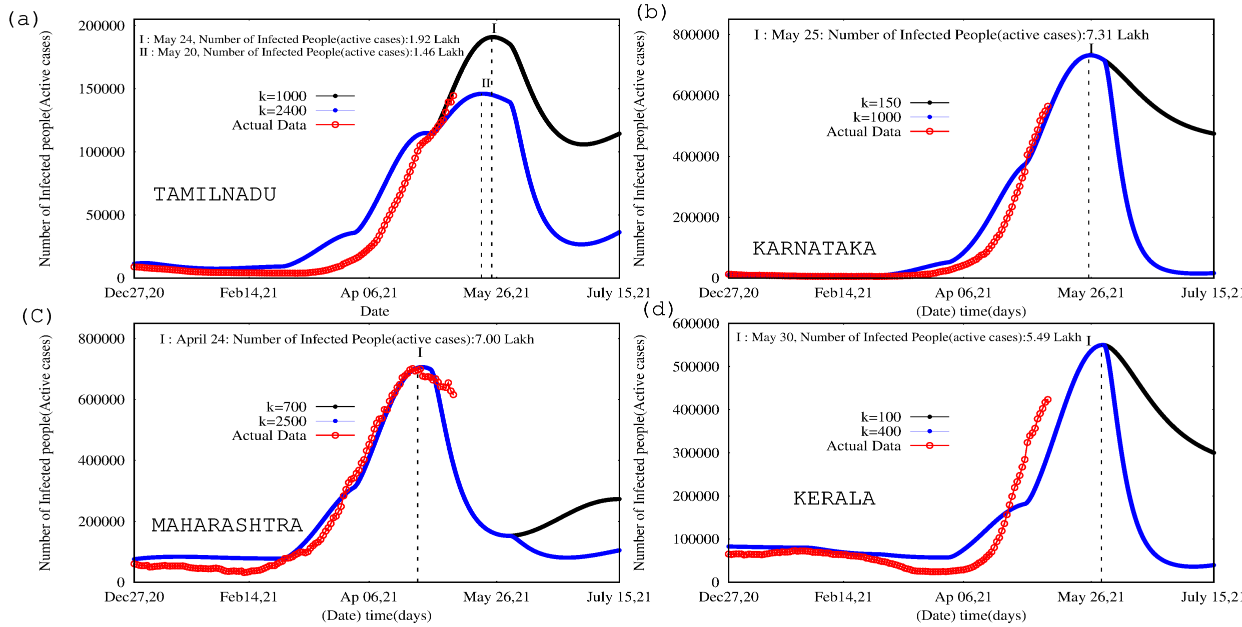

FIG. 2. Numerical simulation of the currently infected people (after removing the number of recovered/deceased people on a particular day) in the various states of India incorporating governmental action strength α, and different values intensity of the individual reaction k : (a) Tamilnadu (α=0.12), (b) Karnataka ($\alpha = 0.2$), (c) Maharashtra ($\alpha = 0.12$) and (d) Kerala ($\alpha = 0.12$. The curves represent the numerical simulation of the number of infected individuals (active cases) from Dec 27,2020 to July 15,2021 with respect to the values of government action strength and various values of intensity of the individual reaction in the SEIR mathematical model (1)-(2). Data available between Dec. 2020 to April 2021 are taken for fitting the parameters. The red curve with circles corresponds to that the actual number of infected individuals. The vertical black dotted lines along with label I and II denote the predicted maximum number infected individuals (active cases).

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