Covid-19 Transmission Dynamics During the Unlock Phase and Significance of Testing

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SUPPLEMENTARY INFORMATION

The lockdown starting date for India is 25th March [1-3] and this date was used as the first critical time-point for simulation. But the USA did not impose any nationwide lockdown and lockdown dates varied from state to state, and even the date was different between two cities. For example, the lockdown starting dates for California, Texas, Florida and New York were March 19, 19, 30 and 22, respectively [4-10]. These four states are now on the top of the table for COVID-19 confirmed cases in the USA [11-13] and contains almost 50% of the total cases. Here, we chose 19th March as the lockdown starting date for the USA and this date was used as the first critical time-point. The unlock stage (ULS) began from the unlock start date, which is refer as the third critical point. The unlock started in India from 1st June [14,15], which is the third critical point for India. The reopening started in California, Texas, Florida and New York are May 8, 1, 1 and June 8 respectively [16-24]. In our study, May 8 is considered as third critical point for the USA.

SUPPLEMENTARY METHODS

S1 Estimation of parameter for model analysis

Simulation of the model for each country was done separately. The simulation started with the time-point when the first confirmed case was reported [12,13] and continued till October 9, 2020. As a first step, the entire study period was divided into three segments by the lockdown starting and removal dates of each country, and termed them as before lockdown stage (BLS), lockdown stage (LS) and unlock stage (ULS). We tried to fit the actual data of BLS, LS and ULS periods separately with the simulated data. With an initial parameter set we obtained a good fit for BLS (R-squared value > 0.9) between the simulated and actual data [12,13]. However, the model does not show a good fit with the LS data [25,26].

This is because lockdown has its effect on some parameters. For example, the value of ν, measuring the strength of lockdown, will certainly increase as the lockdown period becomes longer. Thus it was difficult to get a good fit with a single parameter set for LS data. We, therefore, divided the LS data into small windows and tried to fit the model. We looked for minimum number of windows and allowed changes in minimum number of parameters. We observed that minimum two windows are required to fit the model with the LS data. So, we divided the lockdown stage (LS) into two parts, viz. early lockdown stage (ELS) and later lockdown stage (LLS) by second critical time point to obtain a better fit of the actual data. There is no particular date for the second critical time point, so, we first randomly chose a time point (Supplementary Table S1) as its initial guess and also manually searched initial parameters corresponding to ELS and LLS that give a good fit (R-squared value >0.9) between the simulated and actual data [12, 13]. The only restriction posed during the parameter selection for variation is that the number of parameter should be the minimum most and for that global sensitivity analysis was applied. GSA was performed by using Partial Ranked Correlation Coefficient (PRCC) technique (see Supplementary methods S2) and got six sensitive parameters (α, ξ, β_0, ν, δ_d and μ_d) of the system (1) (Supplementary Figure S1). However, we excluded ξ as it dependants on latent period of the infection and difficult to control. So, the five parameters were used as minimal set of varying parameters. It is worth mentioning that the strength of lockdown in LLS is higher than its immediate early stage. Thus, we varied the parameter values of ν in the range $0.5<\nu<1$ and $0<\nu<0.5$ for LLS and ELS, respectively, and set $\nu = 0$ for BLS.

The initial parameter set was obtained by varying the minimal parameter set for both these countries, see supplementary Table S1. We used this initial parameter guess to get an optimal parameter set by using the "lsqcurvefit" function from the Optimization Tool- box of MATLAB (see Supplementary Methods S3). Next we seek for the optimum value of the second critical time point that gives the best result in terms of curve fitting. The Matlab code "lsqcurvefit" couldnot be used to find the optimal value of the second critical time point because it uses floating numbers in each iteration step. Thus, we defined a new measure MNED using the euclidean distances between the simulation and actual data (see Supplementary Methods S4). We varied the time-points around the initial guess and mea- sured MNED and the second critical time point was selected based on the lowest MNED. For India and USA, the second critical time points are 45 days and 25 days after the lock- down starting date (Supplementary Figure S2) and the corresponding optimal parameter set is given in Table 1.

For the unlock stage the disease spreading rate of the detected infected individuals is restricted to the rate of LLS, while the undetected infected individuals is assumed to transmit the disease with a rate same as ELS. Accordingly, we split β_0 and ν as β_01 and ν_1 for detected class and β_02 and ν_2 for undetected class and fixed them as in LLS and ELS for the two classes respectively. To get the good fit for this stage we varied some parameters with initial guess as given in Supplementary Table S1. Further "lsqcurvefit" function was applied to get the optimal parameter set for this period (see Table 1). With this optimal parameter set, the model (1) was simulated for both the countries and the results were compared with the available data (see Figure 2).

S2 Sensitivity analysis

The Global Sensitivity Analysis (GSA) of a system helps to identify the parameters that have significant effect on the system dynamics and can be used as controlling parameters. Here, we used Partial Ranked Correlation Coefficient (PRCC) technique for the GSA. Latin Hypercube Sampling (LHS) was used to randomly generate vectors of parameter set which were further used for each run of PRCCs calculation [25]. Over 10,000 parameter sets were generated through LHS between the 5 fold up-down range of each parameter, except for γ, ξ, ω and ν, whose upper bounds were set to 1 following the model assumptions. For each parameter set, the system was run for desired time and the maximum level of all the state variables were noted. Then PRCCs were calculated for the parameters with the maximum level of the desired state variables.

S3 Estimation of optimal parameter set

To get the optimal parameter set, ”lsqcurvefit” function from the Optimization Toolbox of MATLAB was used. Basically, ”lsqcurvefit” attempts to computes those parameter sets which will give the minimum value of the expression

$$\phi = \sum_i \left(Y_i - \hat{Y}_i \right)^2 ,$$

where Y_i is the actual value at the ith data point and $\hat{Y}_i$ is the predicted value for any parameter set. Here we have to define a set of lower and upper bounds on the parameter set so that the solutions lie in that range. Also, in the input arguments of this function, the

Algorithm that we want to use for the optimization can be defined. In our case, Y is a matrix of temporal data of total confirmed cases, total recovered cases and total death cases, and $\hat{Y}$ returns the time-series simulation for I_d, R_d and D_d, with inputs initial parameter guess and total time span as total number of data point. Here, ”trust-region-reflective” [26] algorithm

was considered for the optimization and the bounds of the parameters were defined by the two fold up-down values of the initial values of each parameter. As the values of α, γ, ξ and ω can’t exceed 1 (see the model assumptions), so the upper bounds were set to 1 for these parameters. Besides these, the upper bound for ν was set 0.5 for the BLS, and the lower bound of ELS was set 0.5.

S4 Calculation of mean normalized Euclidean distances (MNED)

The normalized Euclidean distance between two vectors *x* and *y* are evaluated by

$$\frac{1}{2} \times \frac{std(x-y)^2}{std(x)^2 + std(\mathrm{y})^2},$$

where *std*(*x*) denotes the standard deviation of the vector *x*. Here, we have calculated the normalized Euclidean distances between simulation time-series results of (I_d+R_d+D_d), R_d and D_d with the corresponding available data of total confirmed cases, total recovered cases and total death cases and then obtained their mean values to get the mean normalized Euclidean distance (MNED).

SUPPLEMENTARY FIGURES AND TABLES

Table S1: Initial parameter and second critical time-point guess for India and US which gives a good fit between simulated and actual data (R-squared value > 0.9). We were assumed that the second critical time points will lie between the ranges of 2-4 week after lockdown starting date.

Parameter	India	USA
l	6	6
γ	0.4	0.25
ξ	0.3	0.33
ω	0.4	0.25
δ_u	0.033	0.02
μ_u	0.001	0.002
Before lockdown stage (BLS)		
α	0.1	0.068
β_0	0.9	0.9
v	0	0
δ_d	0.01	0.0018
μ_d	0.0026	0.004
Early lockdown stage (ELS)		
α	0.25	0.14
β_0	0.9	0.8
v	0.3	0.2
δ_d	0.02	0.01
μ_d	0.006	0.0085

Later lockdown stage (LLS)		
α	0.23	0.04
β_0	0.64	0.29
ν	0.5	0.6
δ_d	0.046	0.0075
μ_d	0.0026	0.0025
Unlock stage (ULS)		
$\beta_0 1$	0.62	0.4
ν_1	0.53	0.5
$\beta_0 2$	0.659	0.62
ν_2	0.41	0.31
α	0.228	0.04
γ	0.34	0.4
ω	0.33	0.4
δ_d	0.048	0.01
δ_u	0.04	0.033
μ_d	0.0023	0.00035
μ_u	0.0012	0.002
Second critical time-point (Number of days after lockdown starting data)		
Initial guess	21	21

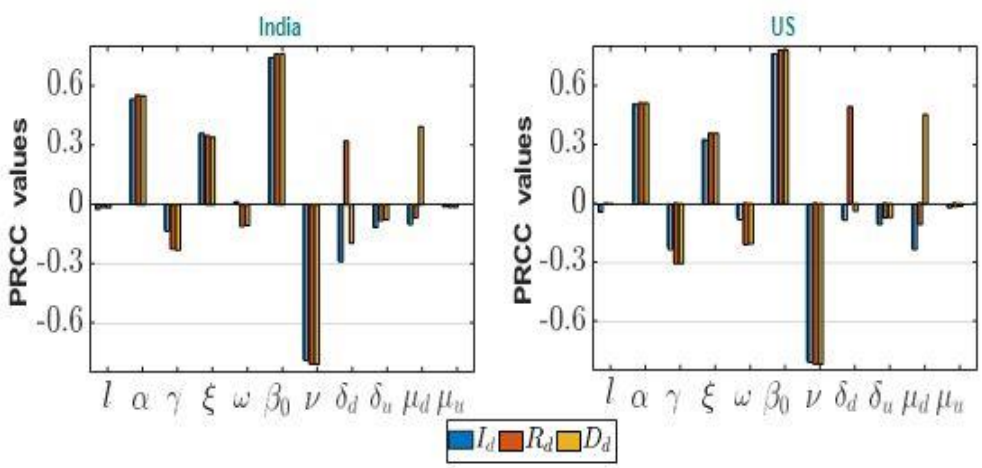

Figure S1: Global sensitivity analysis (GSA) was performed for the two countries to get the minimal varying parameter set. PRCC values of each parameter are represented by the length of the bar for each of the state variables. There are six common parameters (α, ξ, β_0, ν, δ_d and μ_d) that are sensitive to both countries.

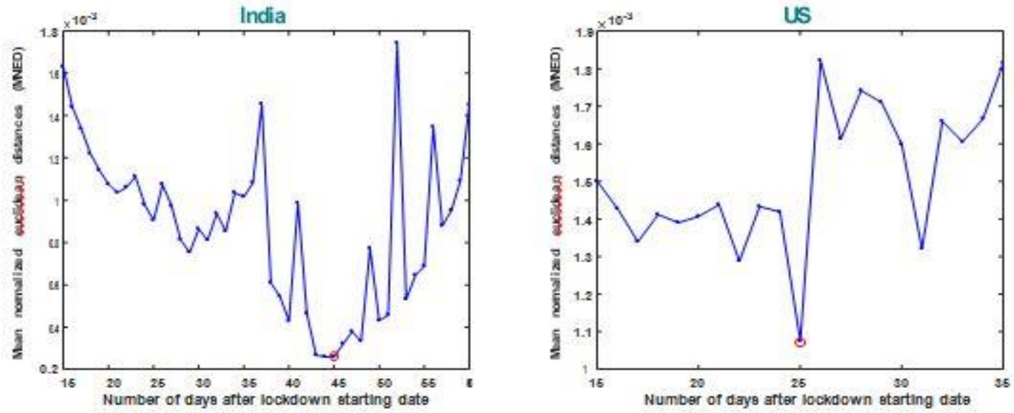

Figure S2: Variation in the mean normalized Euclidean distances (MNED) between simula- tion result and actual data with respect to the changes in second critical time-point around the initial guess. Initial guess of second critical time-points for both India and US were 21 days after the lockdown starting date. Here, the red circled points represent the day where minimum value of MNED were obtained and these dates were further selected as the revised second critical time-point.

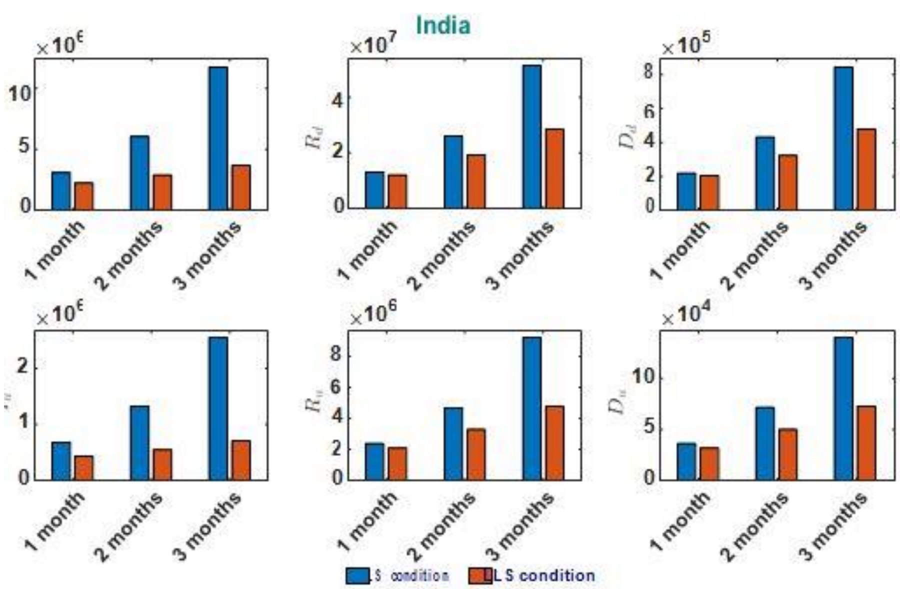

Figure S3: Predicted cases for detected and undetected infectious compartments in India after one, two and three months under two different parametric situations. The blue bars represent the cases if parameters take the ULS values, and the red bar represents the same if parameters take the LLS values (see Table 1).

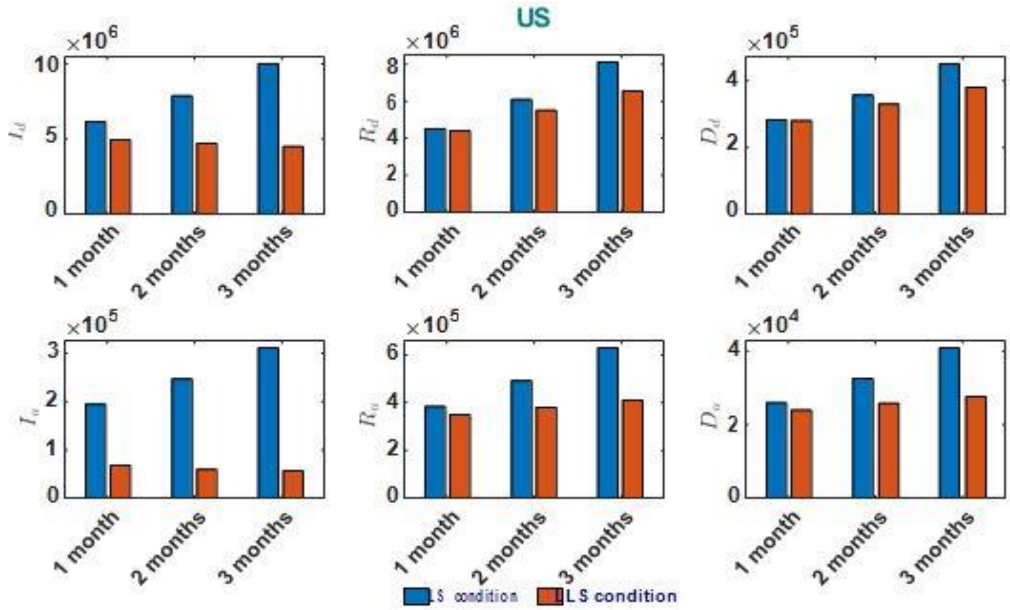

Figure S4: Predicted cases for detected and undetected infectious compartments in US after one, two and three months under two different parametric situations. The blue bars represent the cases if parameters take the ULS values, and the red bar represents the same if parameters take the LLS values (see Table 1).

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