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Original Article

Healthcare impact of COVID-19 epidemic in India: A stochastic mathematical model

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ABSTRACT

Background: In India, the SARS-CoV-2 COVID-19 epidemic has grown to 1251 cases and 32 deaths as on 30 Mar 2020. The healthcare impact of the epidemic in India was studied using a stochastic mathematical model.

Methods: A compartmental SEIR model was developed, in which the flow of individuals through compartments is modeled using a set of differential equations. Different scenarios were modeled with 1000 runs of Monte Carlo simulation each using MATLAB. Hospitalization, intensive care unit (ICU) requirements, and deaths were modeled on SimVoi software. The impact of nonpharmacological interventions (NPIs) including social distancing and lockdown on checking the epidemic was estimated.

Results: Uninterrupted epidemic in India would have resulted in more than 364 million cases and 1.56 million deaths with peak by mid-July. As per the model, at current growth rate of 1.15, India is likely to reach approximately 3 million cases by 25 May, implying 125,455 (±18,034) hospitalizations, 26,130 (±3298) ICU admissions, and 13,447 (±1819) deaths. This would overwhelm India's healthcare system. The model shows that with immediate institution of NPIs, the epidemic might still be checked by mid-April 2020. It would then result in 241,974 (±33,735) total infections, 10,214 (±1649) hospitalizations, 2121 (±334) ICU admissions, and 1081 (±169) deaths.

Conclusion: At the current growth rate of epidemic, India's healthcare resources will be overwhelmed by the end of May. With the immediate institution of NPIs, total cases, hospitalizations, ICU requirements, and deaths can be reduced by almost 90%.

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Introduction

The World Health Organization declared COVID-19 a pandemic on 11 March 2020.[1] Worldwide it has exploded to 784,794 cases and caused 37,788 deaths by 30 Mar 2020.[2] In India, the first case was reported on 30 Jan. By 30 Mar, India had reported 1251 cases and 32 deaths.[3]

The spread of any epidemic depends on the infectivity of the pathogen and the available susceptible population. For a novel infection, when disease dynamics are still unclear, mathematical modeling estimates the number of cases in worst- and best-case scenarios. It can also help estimate the effect of preventive measures adopted against COVID-19. With suppressive strategies, the aim is to maintain the effective reproduction number (R) below 1, to prevent further spread of infection, while in a mitigation strategy, the aim is to blunt the effect of the epidemic.[4] Nonpharmacological interventions (NPIs) utilized to contain epidemics (social distancing; closure of schools, universities, and offices; avoidance of mass gatherings, community-wide containment, etc.) may be applied to the general population, contacts of cases (contact-tracing, surveillance, quarantine), and the cases themselves (early reporting, isolation).[4,5]

India appears to be in early stages of the epidemic. It is important to predict how the disease is likely to evolve among the population. This will help in estimation of healthcare requirements and permit a measured allocation of resources. Considering the differences in the way COVID-19 has spread in different countries, any planning for mounting a fresh response has to be adaptable and situation-specific. When the actual numbers are relatively few, a mathematical simulation approach is best suited toward understanding this epidemic and formulating an appropriate response.

Hence, we decided to create an early stochastic mathematical model of the COVID-19 epidemic in India with the objective of determining its magnitude, assessing the impact on healthcare resources, and studying the effect of certain NPIs on the epidemic.

Material and methods

Epidemiologically, infectious diseases can be studied mathematically using compartmental models.[6] The SEIR model divides the population into Susceptible, Exposed, Infectious, and Recovered compartments (Fig. 1). The flow of individuals through these compartments was modeled using a set of differential equations (Table 1). The model assumes a completely susceptible population (S) with homogeneous mixing. The disease has an incubation period after which an exposed individual becomes infectious. Susceptible individuals become infected at a rate, β, by infectious individuals. The number of exposed individuals is captured by the term βIS. These individuals are removed from the (S) compartment and added to the Exposed (E) compartment. Once infected, the individual remains exposed for the incubation period before becoming infectious. Exposed individuals are thus removed from the E compartment at a removal rate of ε, which is 1/incubation period, and are added to the Infectious (I) compartment. To model the effects of isolation, wherein infectious individuals are isolated so that they are unable to infect the susceptible population, we added a Quarantine (Q) compartment. A fraction (q) of individuals from the (I) compartment move to the Q compartment, once they are isolated/quarantined. Those remaining in the I compartment recover at a rate γ, equal to 1/infectious period, or die at a rate d, equal to the disease-related death rate. Individuals from the Q compartment recover after the period of quarantine and are removed at a rate, qt, equal to 1/period of quarantine, or die at the disease-related death rate, d. The Q compartment captured the hospital or home quarantine of infective individuals. The dynamics of transition to and from this compartment was thus captured using the proportion of infected persons quarantined and the period of quarantine.[7]

A stochastic model using Monte Carlo (MC) simulation was created using MATLAB/SIMULINK Release 2018b (The MathWorks, Inc., Natick, Massachusetts, United States).

Assumptions

We assumed that the total population in the model was fixed. Modeling of the data was based on cases in India on 21 Mar 20. It was assumed that all persons are susceptible across all age groups and there is random movement of individuals within the population. On recovery from infection, individuals are assumed to be immune to reinfection in the short term. The susceptibility and infectiousness characteristics were assumed to be similar in Indians as the rest of the affected countries (Table 2). The infection fatality rate was calculated to be 0.43% for India based on the published data adjusted for age stratification of Indian population[8] (Table 3). The number of individuals quarantined (Q_0) was assumed to be the sum of the

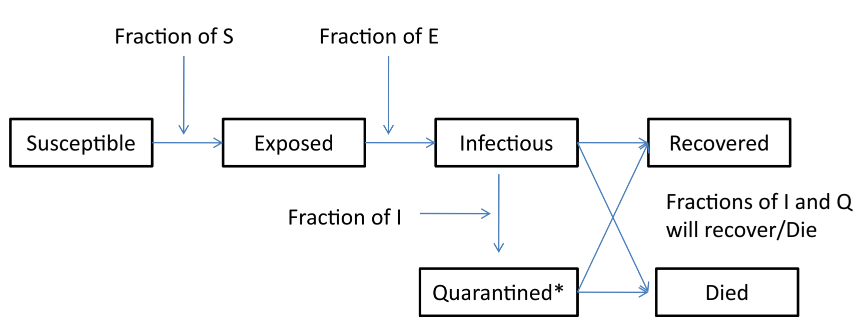

Fig. 1 – The SEIR epidemiological model. *The infectious group when symptomatic is Isolated, when asymptomatic is Quarantined. In practice, only a fraction of exposed are infectious, but ideally all E should be quarantined.

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Table 1 – Differential equations utilized in the creation of the mathematical model.

$\frac{dS}{dt} = -\beta IS$	Where
$\frac{dE}{dt} = \beta IS - \varepsilon E$	$S + E + I + Q + R + D =$ $N(Susceptible + Exposed + Infected + Quarantined + Recovered + Dead = N)$
$\frac{dI}{dt} = \varepsilon E - \gamma I - dI - qI$	$N = Population$
$\frac{dQ}{dt} = qI - qtQ - dQ$	$\beta = R_0 \ \gamma$
$\frac{dR}{dt} = \gamma I + qtQ$	$R_0 = BasicReproductionNumber$
$\frac{dD}{dt} = dI + dQ$	$\varepsilon = \frac{1}{incubation} period$
	$\gamma = \frac{1}{infectious} period$
	$d = death\ rate$
	$q = fraction\ ofactive\ cases\ quarantined$
	$qt = time\ period\ of\ quarantine$

The basic Reproduction number R_0 is the number of secondary cases which one case would produce in a population which is completely susceptible. It depends on contact rate (c), rate of transmission (t) and duration of infectiousness.[7]

number of patients under active treatment and/or quarantined. The initial number of infectious patients (I_0) was estimated from Q_0, assuming that Q_0 is q% of total infectious cases ($I_0 + Q_0$). Initial numbers of quarantined, recovered, and dead were taken from data published by the Ministry of Health and Family Welfare (MOHFW), Government of India, on 21 Mar 20.[3]

Mathematical model

The transition dynamics between the SEIR and Q compartments was modeled in SIMULINK. The model was integrated using a Fixed-step ODE8 (Dormand-Prince) solver. Ten different scenarios were created by varying values of the fraction of infectious cases being isolated, ranging from no isolation to 100%, with simulation in steps of 10%. Each scenario was run using MC simulation, which was repeated a 1000 times. Confidence intervals (95%) of infectious cases were analyzed in MATLAB. Effect of various NPIs such as social distancing, etc., which help reduce the transmissibility of the pathogen, are reflected in the effective reproduction number and were not modeled separately.

Table 2 – Table of assumptions.

Parameter	Value	Remarks
Incubation period ($1/\varepsilon$)	Mean = 5.1 days,[9] shape = 0.1	Gamma distributed
Infectious period ($1/\gamma$)	Mean = 7 days, shape = 0.1	
Basic reproduction number (R_0)	Mean = 2.28, shape = 0.1	
Mean death rate	0.43%[8]	Calculated
Period quarantined (q_t)	14 days	From MOHFW data on 21 Mar 2020
No of cases quarantined (S0)	249	
No of recovered (R0)	23	
No of deaths (D0)	05	
Population of India (N)	1375.98 million[10]	
Calculated growth rate[a]	1.15 (RandTraingular (1.11, 1.15, 1.19))	Simulated on SimVoi software
Hospitalization rate[4]	4.1% (RandTraingular (3.5, 4.1, 5))	
ICU admission rate[4]	0.88% (Randtriangular (0.75,0.88, 1))	
Death rate[4]	0.43% (Randtriangular (0.38, 0.43,0.53))	

[a] Growth rate was calculated from data available on the Ministry of Health and Family Welfare website from 04 Mar to 22 Mar 2020.

Table 3 – Projected age-stratified impact of COVID-19 on hospitalization, ICU admission, and fatality, in India.

Age group (years)	Indian demographic distribution (%)[10]	Hospitalization rate[4]	ICU admission rate (% of hospitalization rate)[4]	Infection fatality rate[4]
0–9	18.4	0.1	5	0.002
10–19	18.8	0.3	5	0.006
20–29	17.5	1.2	5	0.03
30–39	15.3	3.2	5	0.08
40–49	11.7	4.9	6.3	0.15
50–59	9	10.2	12.2	0.6
60–69	5.8	16.6	27.4	2.2
70–79	2.7	24.3	43.2	5.1
80+	0.8	27.3	70.9	9.3

ICU, intensive care unit.

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Initially, the natural evolution of the epidemic impacting the Indian population was modeled, without catering for any NPI or other interventions. The course of the Indian epidemic was compared with that of other selected countries. Widespread testing was initiated on 02 March, resulting in a surge of detected cases. Hence, the data from 04 Mar to 22 Mar from the MOHFW was utilized for calculating the growth rate. The expected number of hospitalizations, intensive care unit (ICU) requirements, and death rates at the current rate of the spread of the epidemic was modeled stochastically using MC simulations on MS Excel using SimVoi add-in software (Table 2). The impact of various degrees of effective quarantine on the number of people infected was modeled.

Results and discussion

Exponential nature of the epidemic

We estimate that the natural uninterrupted evolution of COVID-19 epidemic in India with an R_0 of 2.28 would have resulted in about 364 million cases and 1.56 million deaths overall, with the epidemic peaking by mid-July, 2020 (Fig. 2). The epidemic is clearly not growing at that rate in India. It has possibly been checked partially by various measures planned and instituted by the government even before the first case arrived in India.

COVID-19 impact worldwide

We then plotted the evolution of the epidemic in various countries and conflated the starting points to compare COVID-19 evolution across diverse populations[9] (Fig. 3a). As India is yet in the early phase, the squiggle was barely discernible. Hence, we graphed the logarithmic scale representation to better compare the nature of growth of the epidemic in India (Fig. 3b). China shows the largest area under the curve but also shows a flattening of the slope, indicating control of spread.

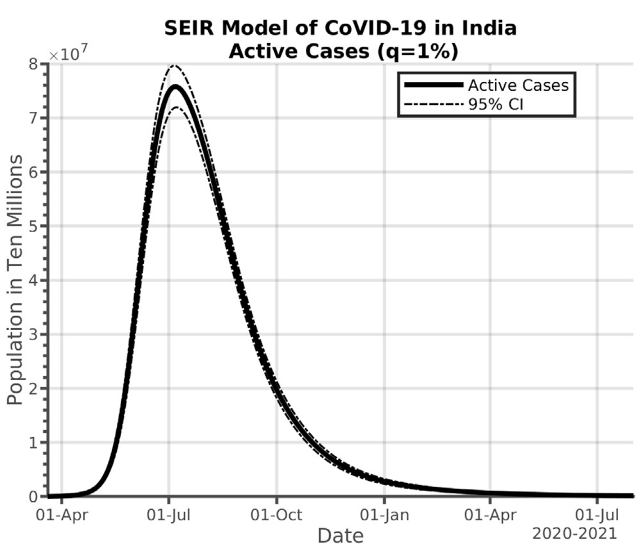

Fig. 2 – Model of natural spread of COVID-19-in Indian population yielding peak of infected cases.

China had initiated stringent and wide-ranging NPI measures which resulted in the reduction of new infections, which is captured in flattening of the shape of the curve. China took the aggressive steps of complete lockdown of Wuhan starting from mid-Jan 2020 and was able to control the epidemic by 8 weeks, where estimated R dropped from 2 to 1.05.[10] South Korea is the only other country among those studied, which has managed to alter its curve. The approach of expanding testing, isolation, and contact-tracing was adopted by South Korea to successfully control the epidemic.[11]

The Indian curve continues to rise, although with a lesser slope, indicating an increasing number of cases in the early phase of the epidemic. In absolute terms, seen as infections per million, India still has a low number of 0.3/million (on 21 Mar 2020) which is two to three orders of magnitude lesser than in other countries which were compared with[9] (Fig. 4). This gives us a unique opportunity to flatten the curve, if we act immediately.

Impact of COVID-19 on healthcare resources and mortality

Scarcity of healthcare resources is a major challenge. The Indian Council of Medical Research (ICMR) estimates that India has about 70,000 ICU beds and even fewer ventilators.[12] We estimate that if around one-third or 25,000 of the available ICU beds were allocated for COVID-19 cases alone, it would result in negative ripple effects among those with other serious diseases requiring ICU care. The current growth rate of the epidemic in India was calculated to be 1.15.[3] It means the number of new cases increases by approximately 15% every day. The model estimates that at the current rate, on 25 May 20, India will approximate 3 million cases (2,979,928 ± 332,369). It would entail 125,455 (±18,034) hospitalizations, 26,130 (±3298) ICU admissions, and 13,447 (±1819) deaths. The requirements would double over the next 5 days, completely overwhelming the Indian healthcare system.

Mortality rates of COVID-19 disease in those older than 60 years are significantly higher (50–1000 times) than in younger age groups[8] (Fig. 5). While the elderly (>60 years) comprise around 10% of the population in India, in our model, they accounted for approximately 43% of all hospital admissions and about 82% each of ICU admissions and deaths. The elderly are most likely to get infected by their household contacts. Hence, special and novel NPIs may have to be developed for them, with a greater focus among their household contacts.

It is therefore imperative that interventions are further scaled up to meet this challenge. We looked at which interventions could possibly be modeled mathematically and settled on quarantine.

Impact of quarantine

Quarantine is an active NPI intended to reduce transmission that shifted a greater percentage of Infectious (I), especially those who were untested, into (Q) compartment. As the number of individuals quarantined increases, the number of freshly infected (and hence the infectious) cases reduces, as they no longer have contact with the susceptible group.

The effectiveness of quarantine depends on the compliance by individuals and public health measures that are

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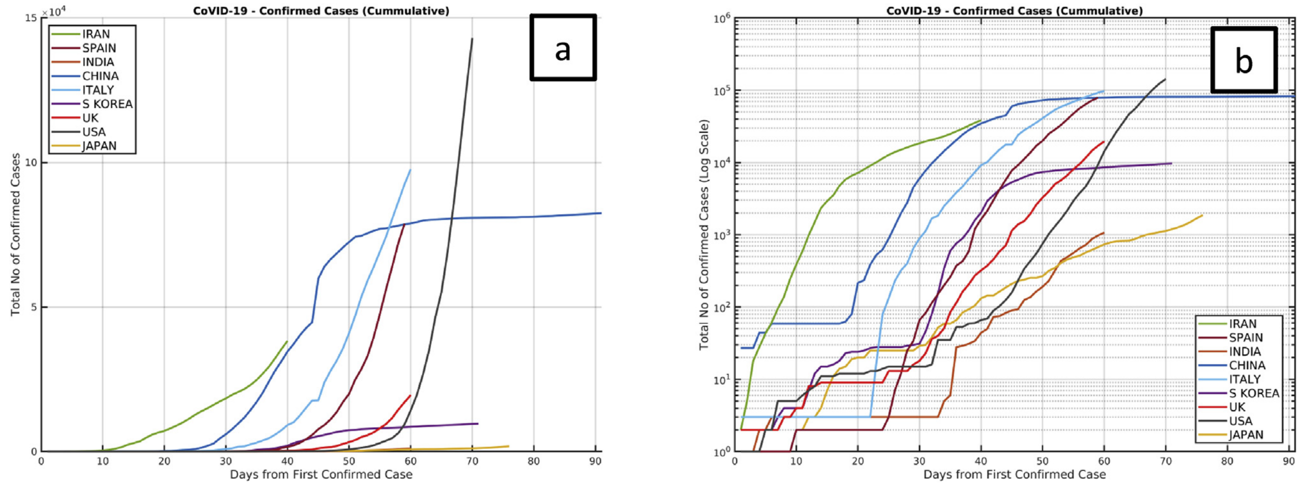

Fig. 3 – COVID-19 growth across countries. (a) Rate of growth; (b) log scale representation.

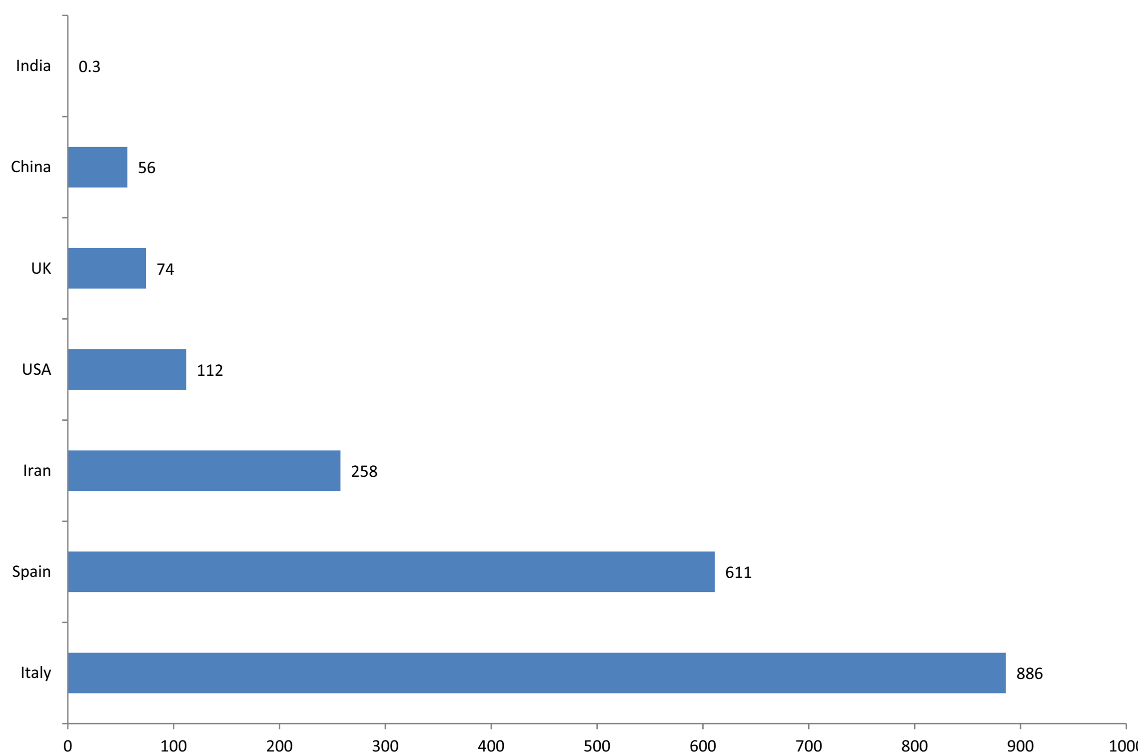

Fig. 4 – COVID-19 cases per million as on 22 Mar 2020.

instituted. This reduction occurs exponentially, resulting in a sharp inflection point when graphed on a log scale (Fig. 6). Our model showed that at 40% compliance, quarantine starts becoming effective. At above 50% compliance, explosive growth of the epidemic is checked and the slope of the epidemic growth curve is reversed (Fig. 7a–d). In the model, we varied the effectiveness of quarantine/isolation of infected cases on 20 March 2020 from almost nil to 100%. This resulted in a dramatic reduction of eventual total cases from 1070 million to 1401, a reduction of six orders of magnitude. This fall in numbers is steepest at 50% (Table 4).

The mathematical model shows that improving effective quarantine/isolation of infective cases with a lockdown would translate to quarantine efficacy of >50% with reversal of the epidemic growth (Fig. 8). The curve would bend within 2–3 weeks of instituting the measures with 241,974 (±333,735) total infections, 10,214 (±1649) hospitalizations, 2121 (±334) ICU admissions, and 1081 (±169) deaths by 25 May 2020. It could be lower if the country collectively achieves quarantine levels above 50%. The numbers infected finally become manageable, reducing from millions to merely thousands. From being completely overwhelmed, India can now look at

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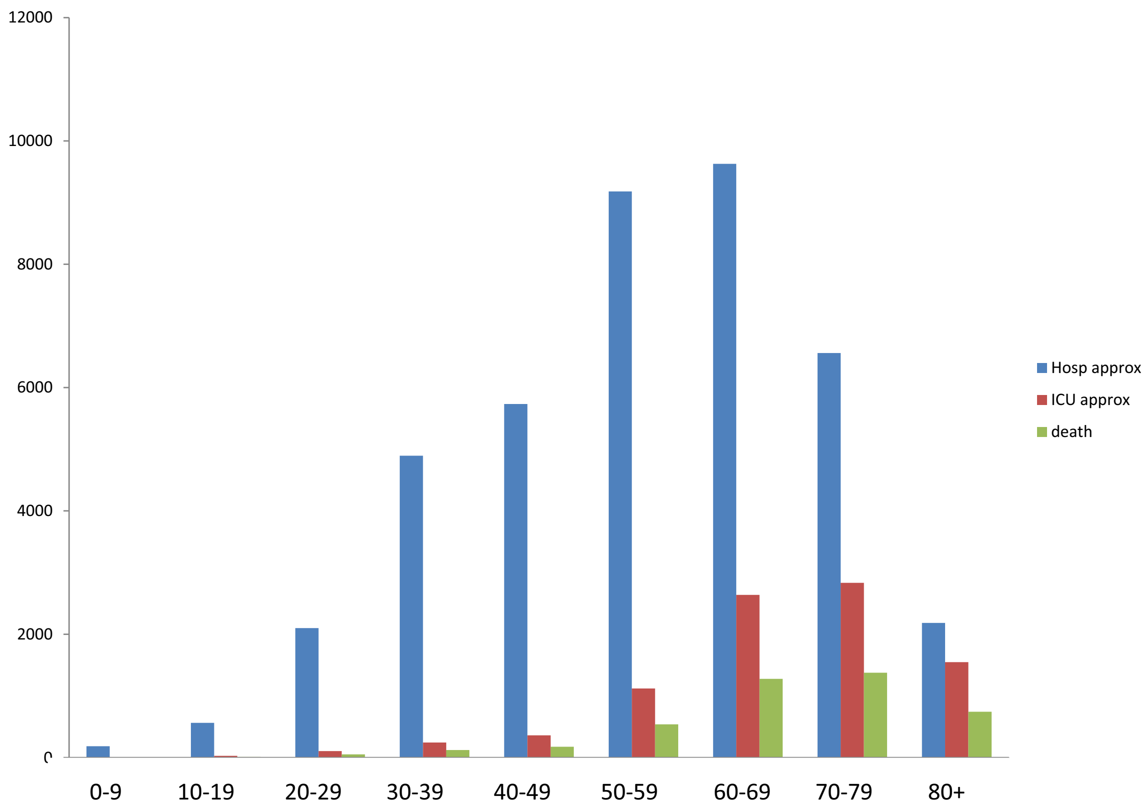

Fig. 5 – Age-stratified hospitalizations, ICU admissions, and deaths on 13 May (1 million cases) at the current growth rate. ICU, intensive care unit.

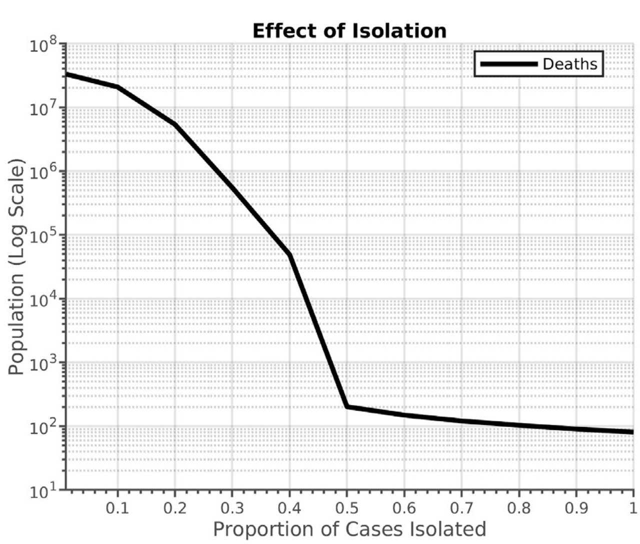

Fig. 6 – Effectiveness of quarantine / isolation (Inflection point achieved at 50%).

setting certain planning targets, where the available healthcare resources are not completely saturated. Each passing day makes the task of controlling the epidemic more out of reach.

In the mathematical model of the epidemic, the infectious group is neatly compartmentalized. In real life, at least 50% of them need to be quarantined/isolated for the graph to reach inflection point. Considering the current rising trend, it appears that more than 50% of the infected persons in the population have not been identified at present. The reasons appear to be twofold. Unlike in the model, the infectious group is not clearly identifiable in the community, as many of them are presymptomatic/asymptomatic or with mild symptoms who do not seek medical care. There are also people with known exposure (e.g., return from foreign travel) who might not effectively submit to self-quarantine. Once community spread commences, it becomes difficult to even identify exposure. It has been estimated from early studies that 40–50% of infectious individuals remain asymptomatic and they are equally infectious as those who are symptomatic.[13–15] Early testing of greater numbers is likely to identify more infective individuals. The ICMR cautiously has recommended an increase in the numbers to be tested.[16] The only way to prevent transmission from undetected infective cases to susceptible population is to implement universal NPI measures.

Impact of NPIs

Among the susceptible, and that includes almost the entire population, it is imperative to act with multiple NPI measures continuously over a prolonged period of time. A group of NPIs, collectively termed distancing measures, attempts to reduce

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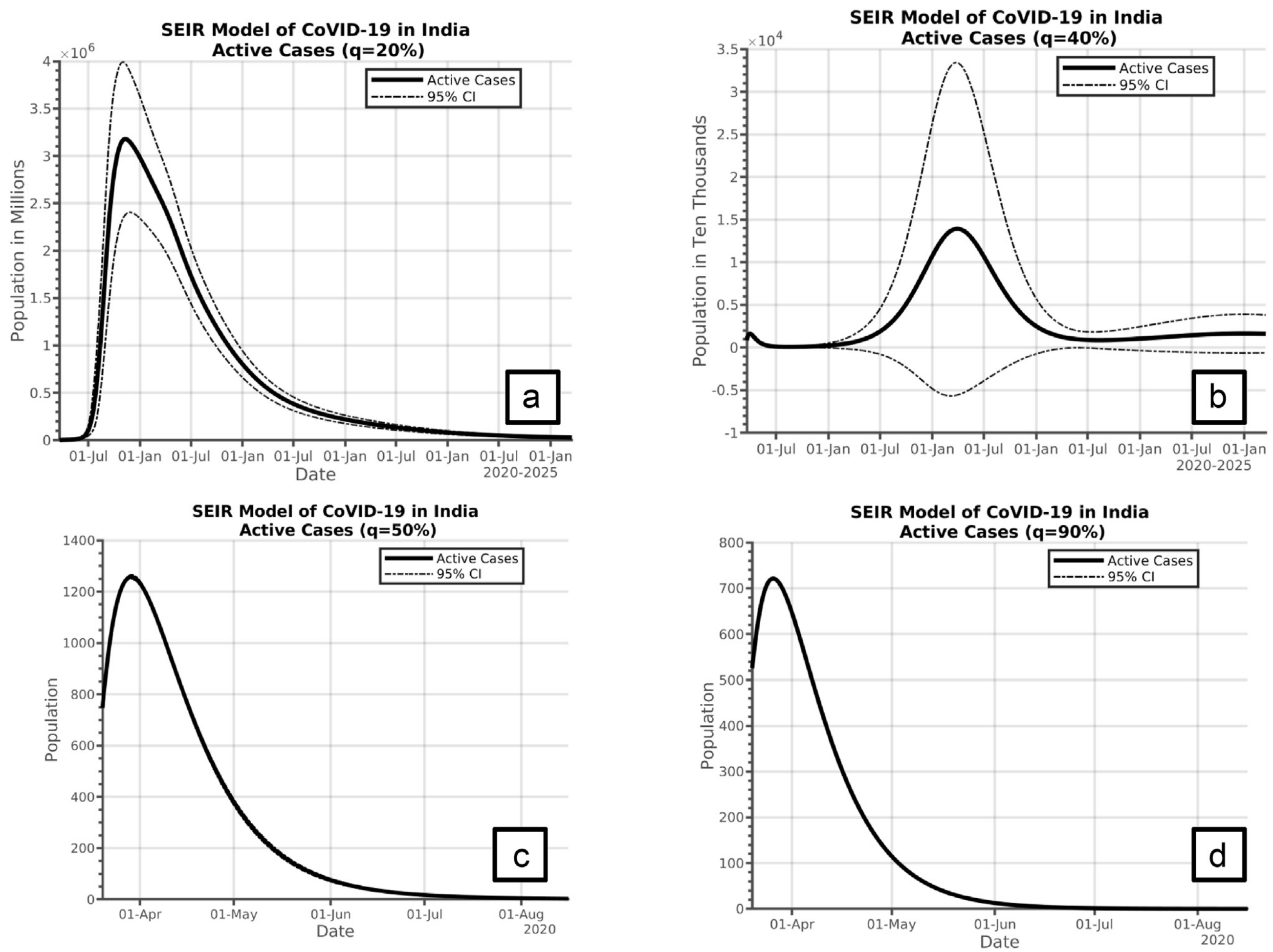

Fig. 7 – SEIR model of COVID-19: peak infections in India at effective quarantine levels of infectious individuals (a) 20%, (b) 40%, (c) 50%, and (d) 90%.

R. These range from (a) social distancing measures such as no handshaking practiced by individuals; (b) working from home, an option available for many types of jobs; (c) closing of educational institutions (schools, colleges etc.); (d) cancellation of mass gatherings (social, entertainment, and religious functions); (e) partial or total closure of malls/markets, which has significant economic impact; (f) reduction or closure of public transportation; (g) voluntary civic shutdown, "Janata curfew," etc. and finally, (h) enforced lockdown as in Wuhan. Complete lockdown represents one extreme of NPI measures but might be the best modality when majority of the

Table 4 – Impact of effectiveness of containment on 20 March 2020 on the total number of cases.

Effective quarantine % (q)	Total infected
0.1%	1070 million
10%	521 million
20%	121 million
30%	15.7 million
40%	1.05 million
50%	4412
60%	2757
70%	2206
80%	1836
90%	1589
100%	1401

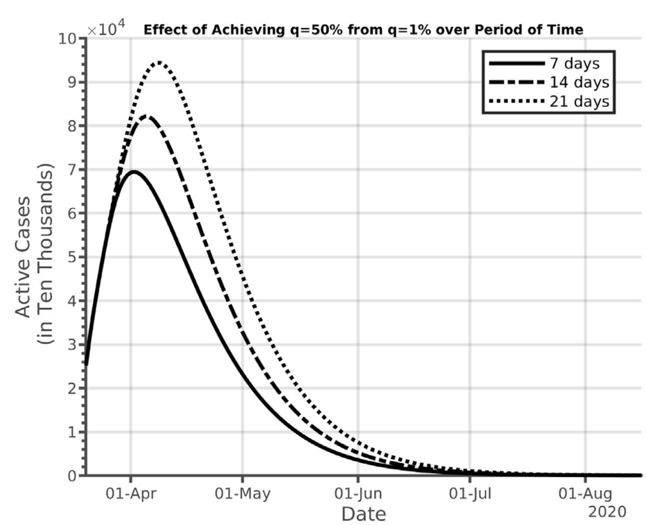

Fig. 8 – Effect of suppressive measures from q1% to q50%, resulting in bending of the curve.

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Table 5 – Likely impact of community containment measures on healthcare utilizations in India by 25 May 2020 (when numbers would be approximately 3 million).

Domains	At current growth rate (1.15)	After lock down (q = 50%)	Percentage reduction
Total cases, mean (±SD)	2,979,928 (±332,369)	241,974 (±33,735)	90%
Hospitalizations, mean (±SD)	125,455 (±18,034)	10,214 (±1649)	
ICU, mean (±SD)	26,130 (±3298)	2121 (±334)	
Deaths, mean (±SD)	13,447 (±1819)	1081 (±169)	

ICU, intensive care unit; SD, standard deviation.

infectious persons are in the community. The only way to reduce the transmission below 50% remains effective community containment, and its effect on the epidemic is critical.

Among the infectious, besides isolation, contact-tracing is a key element in fighting the epidemic. It helps focus attention on tracing and quarantining, as quickly as possible, those whom the infected case might have transmitted the infection to. Maximum returns will be achieved by contact-tracing and quarantine of the asymptomatic exposed individuals. Because identifying infectious cases is difficult, the NPIs have to be targeted at the entire population.

Our model shows that immediate implementation of effective combination of NPIs, including lock down, can result in a drastic reduction in the healthcare requirements arising from the COVID-19 epidemic. If mass community isolation measures succeed in achieving q50% or greater, as per our model, it is likely that the COVID-19 cases, hospitalizations, ICU requirements, and deaths will decline by almost 90% (Table 5). A recent mathematical model published by the ICMR predicted a 62% reduction in cumulative incidence in the optimistic scenario.[17]

COVID-19 is here to stay. In the long term, the only protections against COVID-19 are development of herd immunity or the availability of an effective vaccine. The latter is possibly 12–18 months away. Herd immunity may be achieved when 55–65% of population is infected.[18] This will occur over many months. However, because the epidemic will definitely be partially controlled with implemented measures, it is likely to follow a yo–yo pattern and the herd immunity might take longer to achieve. Hence, until herd immunity is achieved, containment measures, possibly intermittently administered over a prolonged period of time, will required to be in place.

Limitations

As with all mathematical models, ours too has certain limitations. For ease of modeling, we have assumed homogenous distribution of the Indian population that does not capture variations in population density or the urban-rural variations. We have also assumed equal susceptibility to COVID-19, which does not cater for variation in mixing, with stratification for age, occupation, and travel. We have not modeled for pre-existing comorbidities, which alters outcomes. The testing rate is lower in India than in many Western countries, so our absolute numbers might be low. However, we have assumed that even if we increase our testing substantially, following an initial blip, the growth rate will mimic the current growth rate. Finally, the calculated infection fatality rates might be an underestimation, as it is pegged to Western figures, which have better available healthcare facilities.

Our model is based on early data available on public platforms until 21 Mar 20. Future models can include greater granularity as more data become available, and dynamics of the SARS-CoV-2 virus becomes better known.

Conclusions

India is in the early stage of the COVID-19 epidemic, with a lower growth rate than other countries studied. Our mathematical model shows that, unchecked, the epidemic is likely to cross 3 million cases by 25 May 2020 and overwhelm the available healthcare resources. The model also suggests that immediate implementation of NPIs among the general population, including complete lockdowns, has the potential to retard the progress of the epidemic by April 2020 and reduce the COVID-19 cases, bringing down hospitalizations, ICU requirements, and mortality by almost 90%. This will make the epidemic manageable and bring it within the ambit of available healthcare resources in India.

Conflicts of interest

The authors have none to declare.

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