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Comparing COVID-19 vaccine allocation strategies in India: A mathematical modelling study

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ABSTRACT

Background: The development and widespread use of an effective SARS-CoV-2 vaccine could prevent substantial morbidity and mortality associated with COVID-19 and mitigate the secondary effects associated with non-pharmaceutical interventions.
Methods: We used an age-structured, expanded SEIR model with social contact matrices to assess age-specific vaccine allocation strategies in India. We used state-specific age structures and disease transmission coefficients estimated from confirmed incident cases of COVID-19 between 1 July and 31 August 2020. Simulations were used to investigate the relative reduction in mortality and morbidity of vaccine allocation strategies based on prioritizing different age groups, and the interactions of these strategies with concurrent non-pharmaceutical interventions. Given the uncertainty associated with COVID-19 vaccine development, we varied vaccine characteristics in the modelling simulations.
Results: Prioritizing COVID-19 vaccine allocation for older populations (i.e., >60 years) led to the greatest relative reduction in deaths, regardless of vaccine efficacy, control measures, rollout speed, or immunity dynamics. Preferential vaccination of this group often produced relatively higher total symptomatic infections and more pronounced estimates of peak incidence than other assessed strategies. Vaccine efficacy, immunity type, target coverage, and rollout speed significantly influenced overall strategy effectiveness, with the time taken to reach target coverage significantly affecting the relative mortality benefit comparative to no vaccination.
Conclusions: Our findings support global recommendations to prioritize COVID-19 vaccine allocation for older age groups. Relative differences between allocation strategies were reduced as the speed of vaccine rollout was increased. Optimal vaccine allocation strategies will depend on vaccine characteristics, strength of concurrent non-pharmaceutical interventions, and region-specific goals.

Introduction

After first emerging in Wuhan, China in late 2019,(Li et al., 2020) severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the virus that causes coronavirus disease 2019 (COVID-19), has spread rapidly throughout the world causing local epidemics in virtually all countries (Dong et al., 2020). While early, large-scale COVID-19 epidemics occurred primarily in high-income countries in Europe and North America, a significant number of cases and deaths have also now occurred in low- and middle-income countries (Dong et al., 2020). Approximately 1.4 billion people are at risk of SARS-CoV-2 infection in India with many having risk factors for severe outcomes (Nandi et al., 2020).

The first confirmed case of COVID-19 in India was identified in Kerala state on 30 January (Perappadan, 2020). During weeks that followed, several travel-associated cases were confirmed

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throughout the country (Rawat, 2020). To slow the spread of the virus and reduce peak incidence, the central government initiated one of the largest lockdowns in the world on 25 March 2020 comprising non-pharmaceutical interventions (NPIs), including physical distancing and restrictions on non-essential travel (Pulla, 2020). Several analyses indicate that lockdown measures substantially reduced the effective reproduction number (R_t) in the country (Gupta et al., 2020; Kumar et al., 2020; Sardar et al., 2020). However, the lockdown precipitated several secondary effects, including reduced livelihoods, difficulty accessing routine health services, and mass migrations (The Lancet, 2020). Lockdown measures were relaxed beginning on 1 June 2020. As of 12 November 2020, India has reported approximately 8.6 million cases and 130,000 deaths (Dong et al., 2020).

In the absence of a highly effective therapeutic agent for COVID-19, the development of vaccines that provide protection from SARS-CoV-2 infection is a global imperative. An unprecedented effort is currently underway to rapidly develop effective COVID-19 vaccines, with several stakeholders working together to condense the process into months (Graham, 2020). Of the numerous vaccine candidates under development, 11 are in Phase III clinical trials as of November 2020 (Milken Institute, 2020). Five COVID-19 vaccines have been approved for limited use; however, Phase III clinical trial data are not yet available for these vaccines and they have not been prequalified by the World Health Organization (WHO) (Milken Institute, 2020). In India, clinical development is currently underway for multiple candidate vaccines.

New mechanisms are also being established to expedite manufacturing and deployment and support the fair distribution of COVID-19 vaccines (World Health Organization, 2020a). The COVAX Facility is a global risk-sharing mechanism for the pooled procurement of COVID-19 vaccines. Through this mechanism, 92 low- and middle-income countries, including India, are eligible to be supported by the COVAX Advance Market Commitment (AMC), which will pay for the cost of COVID-19 vaccines once COVID-19 vaccines have been licensed and prequalified by the World Health Organization (2020a). Countries participating in the COVAX Facility are encouraged to vaccinate frontline health workers and social care workers first (World Health Organization, 2020b). As the supply of COVID-19 vaccines increases, the distribution of COVID-19 vaccines through the COVAX Facility will continue such that 20% of country populations can be covered, specifically those at increased risk.

In the context of limited supply and to support policies related to COVID-19 vaccine allocation in India, we developed a mathematical model to simulate different vaccine allocation strategies. There remain several unknowns associated with the current COVID-19 vaccine development. Therefore, we assessed these vaccine allocation strategies varying potential vaccine characteristics. We also evaluated the relative reduction in cases and deaths under of varying control measures. The findings of this analysis could also be used by other low- and middle-income countries to inform their COVID-19 vaccine allocation strategies.

Methods

Data collection

Daily and state-specific confirmed incident SARS-CoV-2 infection case data were collected from multiple sources, including the Ministry of Health and Family Welfare, the Indian Council of Medical Research, and a website for crowd-sourced information related to COVID-19 (www.covid19india.com). The data available from this website are collated from public sources and validated by a group of volunteers.

Model of disease transmission

Disease transmission was modelled using an age-structured compartment model, stratified into ten-year age bands (0–10, 10–20, [. . .], 60–70, ≥70 years). The model includes different compartments for each age band and infection state (i.e., S, E, A, I, Q, and R). We assume subjects start susceptible to infection (S) and can become exposed (E) after contact with an infectious individual. After a latent period, exposed subjects either develop an asymptomatic (A) or symptomatic (I) infection, with an age-stratified probability. Subjects with symptomatic infections are hospitalized or choose to self-isolate (Q) at a given rate. Once hospitalized or isolated, subjects either recover (R) or die (D), with an age-stratified mortality rate. Asymptomatic individuals are assumed to have no risk of mortality and simply recover at a given rate. Recovered subjects are assumed to become susceptible at a given rate, reflecting eventual loss of temporary immunity from the infection (Sariol and Perlman, 2020). We assumed that COVID-19 vaccines are allocated gradually into a specific age-defined community at a constant rate.

We simulated two different mechanism through which COVID-19 vaccines could induce immunity (Peiris and Leung, 2020). In one simulation, vaccinated individuals (V) are protected from infection and therefore unable to infect others (i.e., sterilizing immunity). In the other simulation, vaccinated individuals are not protected from asymptomatic infection and therefore can infect others if they become infected (i.e., non-sterilizing immunity). In the latter, if an individual develops an asymptomatic infection after receiving a vaccine that does not confer sterilizing immunity, they are assumed to have a temporary immunity from developing further asymptomatic infections, with immunity waning at the same rate as non-vaccinated subjects who recover from infection. Formulated as a system of differential equations, and using S_i to denote the susceptible population from age group i, for each age group our model comprises:

$$\frac{dS_i}{dt} = \mu R_i - \varepsilon M - \frac{\beta_1}{N}\sum_{j=1}^{K} C_{ij}\ S_i\ \left(A_j + A_j^v + \ I_j\right),$$

$$\frac{dV_i}{dt} = \mu R_i^v + \ \varepsilon M - \frac{\beta_2}{N}\sum_{j=1}^{K} C_{ij}\ V_i\ \left(A_j + A_j^v + \ I_j\right),$$

$$\frac{dE_i}{dt} = \ -\sigma E_i + \frac{\beta_1}{N}\sum_{j=1}^{K} C_{ij}\ S_i\ \left(A_j + A_j^v + \ I_j\right),$$

$$\frac{dE_i^v}{dt} = \ -\sigma E_i^v + \frac{\beta_2}{N}\sum_{j=1}^{K} C_{ij}\ V_i\ \left(A_j + A_j^v + \ I_j\right)$$

$$\frac{dA_i}{dt} = (1-p_i)\sigma E_i - \gamma A_i,$$

$$\frac{dA_i^v}{dt} = \ \sigma E_i^v - \ \gamma A_i^v$$

$$\frac{dI_i}{dt} = p_i\sigma E_i - \ \alpha I_i,$$

$$\frac{dQ_i}{dt} = \alpha I_i - \omega Q_i,$$

$$\frac{dR_i}{dt} = \gamma A_i + (1-\delta_i)\omega Q_i - \mu R_i,$$

$$\frac{dR_i^v}{dt} = \gamma A_i^v - \mu R_i^v,$$

$$\frac{dD_i}{dt} = \delta_i \gamma_2 Q_i,$$

where $1/\mu$ is the average length of immunity, β_1 is the force of infection, N is the total population size, $1/\sigma$ is the average latent period, p is the proportion of infections which are symptomatic, $1/\gamma$ is the average asymptomatic recovery time, $1/\omega$ is the average time from isolation to recovery for a symptomatic infection, $1/\alpha$ is the average time until a symptomatically infectious subject self-quarantines or is hospitalized, and δ is the likelihood of death given symptomatic infection. C_{ij} is the relative frequency of contact between age group i and age group j. For the simulation where vaccines confer non-sterilizing immunity, $\beta_2 = \beta_1$ and E^V, A^V, and R^V denote subjects who are exposed, asymptomatic, and recovered, respectively. For the simulation where COVID-19 vaccines provide sterilizing immunity, $\beta_2 = 0$, meaning those who are vaccinated cannot become infectious. In both cases, vaccines are assumed to be rolled out gradually, with M doses available each day, and an efficacy of ε. We assumed that subjects moved to the vaccinated (V) compartment only once they received all doses of the COVID-19 vaccine. Figure 1 is flow diagram of transitions within the model.

Contact matrices (C) were estimated from social mixing patterns in the Indian population (Prem et al., 2017). Estimates were broken down into four categories, representing the mixing patterns in different environments: (1) "at home", (2) "at school", (3) "at work", and (4) "other"; with C representing the summation of the mixing matrices. In normal scenarios (i.e., no control measures), each mixing pattern was equally weighted. Under strong control measures weights of 1.21, 0.56, 0.0, and 0.45 were used for "at home", "at work", "at school", and "other" matrices, respectively, based on estimates from Google's mobility data during the lockdown period (March 25–May 31, 2020) (Aktay et al., 2020). Moderate control measures were simulated using the average between no control and strong control measure weights.

All parameters except β were estimated based on prior studies, with a full list of parameters and their sources given in Table 1. β values were estimated based on fits of the model-simulated, hospitalized or self-isolated population numbers (Q) against confirmed active infection case numbers, between 1 June and 31 July (i.e., after the lockdown period). Given variability in social mixing patterns immediately after the national lockdown, β values were estimated assuming moderate control measures and no control measures during this period. Similar fits were obtained when fitting model-simulated deaths (D) against reported deaths and when simultaneously fitting D and Q against infection and death case numbers (supplemental material). Parameter fitting was performed using *MATLAB's Statistical Toolbox* with an example data fit presented in the supplemental materials. All models were simulated in MATLAB and use forward Euler discretisation for the differential equations, with a timestep of one day.

Vaccination strategies

Four age-based vaccination strategies were considered: (1) vaccines are distributed evenly across the entire population or were first distributed to those who were: (2) 20–40 years, (3) 40–60 years, or (4) ≥60 years. In strategies 2–4, following vaccination of the target age group to the assumed vaccine coverage, vaccine doses were allocated to the remaining population proportional to the size of the remaining age-groups. Simulations were performed using a range of vaccine efficacies and assuming a fixed number of doses available each day.

Within this framework, simulations were performed using efficacy, age-specific population coverage ranging from 0 to 100% and considering vaccines that provide sterilizing and non-sterilizing immunity. Dose availability was assumed constant over time, reflecting the market pressures of acquiring vaccine doses,

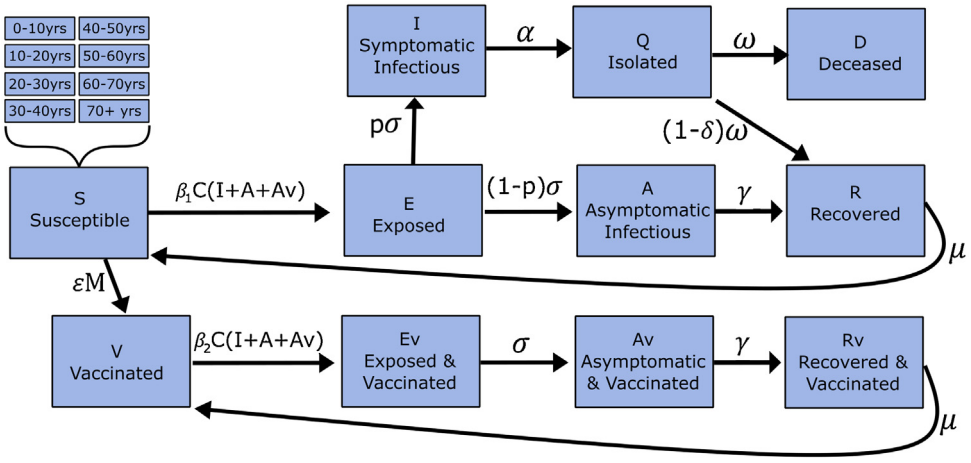

Figure 1. Schematic of model transmission dynamics.
Subjects may move from susceptible to exposed to symptomatic or asymptomatic infectious. Asymptomatic infectious are assumed to always recover, while symptomatic infectious first quarantine, before recovering or dying and (if recovered) eventually losing immunity. Each major compartment comprises eight sub-compartments, comprising age groups (0–10, 10–20, [. . .] 60–70, ≥70 years). Rates of symptomatic infection (p) and death (δ) vary by age group. Contact between susceptible and infectious populations is age-structured, proportional to the estimated contact pattern matrix (C). Under a progressive rollout scheme, M individuals are vaccinated each week, at an efficacy of ε. If the vaccine confers non-sterilizing immunity, individuals can become exposed and develop asymptomatic infections, before recovering and eventually losing infection-driven immunity. For those vaccines that do not confer sterilizing immunity, $\beta_2 = 0$; meaning vaccinated individuals no longer contribute to transmission dynamics.

Table 1
Model parameters and region-specific R0 estimates. R0 was estimated during the 2 months post-lockdown (June 01–July 31, 2020), with either moderate or no non-pharmaceutical interventions.

R_0 Estimates			
Region	Population (millions)	Value (no NPIs)	Value (moderate NPIs)
Uttar Pradesh	204.2	2.41	3.22
Maharashtra	114.0	2.20	2.89
Bihar	104.1	2.36	3.15
West Bengal	90.3	2.33	3.10
Madhya Pradesh	72.6	1.81	2.39
Tamil Nadu	72.1	2.31	3.12
Rajasthan	68.5	2.00	2.59
Karnataka	64.1	3.74	4.95
Gujarat	60.4	1.89	2.49
Andhra Pradesh	49.5	2.93	3.92

Other model parameters		
Parameter	Value	Reference
$1/\sigma$ (latent period)	5.1 days	Lauer et al. (2020)
$1/\gamma$ (recovery period)	21 days	Bi et al. (2020)
$1/\alpha$ (pre-isolation infection period)	4.6 days	Bi et al. (2020)
$1/\omega$ (post-isolation recovery period)	16.4 days	Bi et al. (2020)
$1/\mu$ (immunity duration)	1 year	Estimated (other values in supplemental material)
p (proportion of symptomatic infections)	Age-specific	Davies et al. (2020)
Δ (case fatality rate)	Age-specific	Laxminarayan et al. (2020)

and the logistic pressures of distributing these doses. Dose availability was expressed as the percentage of the population which could be vaccinated each month, with simulations using values from 2 to 15%, reflecting an approximate time of between six months to four years to vaccinate to 100% of the target population. Results are presented over a five-year period, reflecting an approximate upper bound on the likely time to achieve target vaccine coverage (i.e., target coverage can be achieved in less time). Nevertheless, given potential changes in vaccine availability, we also present results over a one-year time period for comparison (supplemental material).

Results

Parameter estimates

R_0 values were estimated for the 10 most populous states within India, assuming moderate control measures and no control measures. Estimates are given in Table 1, with mean R_0 values of 2.4 assuming no control measures and 3.2 assuming moderate control measures during the lockdown period. We used the former as the base case value in our simulations. Minimum and maximum values were 1.8 and 5.0 respectively, with results using these values in the supplemental materials. The values in Table 1 are consistent with R_0 values reported for other countries (Gatto et al., 2020; Sanche et al., 2020; Wu et al., 2020; Zhao et al., 2020). Within our model, the implementation of moderate and severe control measures led to a 23% and 44% relative reduction in R_0, respectively.

Vaccine strategy simulations

Four vaccine strategies were simulated under variations in dosage availability, target group coverage, vaccine efficacy, effect on transmission (i.e., sterilizing or non-sterilizing immunity), and the implementation of other control measures (i.e., no lockdown, moderate lockdown, or strong lockdown). Example epidemic curves for COVID-19 vaccines that confer sterilizing and non-sterilizing immunity are given in Figure 2. Regardless of vaccination strategy and immunization coverage in the target population, the initial infection wave occurs at a similar time, though with varying severity based on strategy. However, COVID-19 vaccines that confer sterilizing immunity appear to minimize the extent of future infection waves. In both cases strategy 4 (i.e., prioritizing individual $\geq$60 years) leads to the greatest reduction in deaths; however, all vaccination strategies produce significant benefits comparative to no vaccination.

Within Figure 3, we present the estimated reduction in deaths and symptomatic infections over a five-year period using each of the four vaccination strategies, under varying efficacy, control measures, and rollout speeds. All results are presented relative to the outcomes with no vaccination, using the same R_0 value, and with no control measures. Simulations were performed using an R_0 of 2.4 (i.e., the mean R_0 value in 10 states) and assume a target COVID-19 vaccine coverage of 75%. Results in Figure 3 illustrate that prioritizing vaccine allocation among older adults consistently results in the greatest reduction in deaths, regardless of vaccine efficacy, control measures, rollout speed, or immunity type. Conversely, all four strategies result in extremely similar reductions in symptomatic infection rates, with the optimal strategy being dependent on the specific implementation and vaccine. The relative benefit of prioritizing vaccine allocation among older adults compared to other strategies is highest under slower rollout speeds, while overall benefit is greatest the faster the rollout speed.

Overall reduction in deaths is strongly limited by vaccine efficacy, and is strongly influenced by control measures, with more severe measures leading to greater reductions. Similar patterns were seen with different R_0 values, target coverages, and immunity assumptions (supplemental materials). Similar patterns were also seen when assuming imperfect self-isolation of symptomatically infectious individuals (supplemental materials), and when assuming some degree of disease transmission by pre-symptomatic individuals (supplemental materials).

While R_0 values, vaccine efficacy, and other vaccine characteristics (i.e., sterilizing versus non-sterilizing immunity) all influence strategy effectiveness, in application these factors are immutable from the perspective of policy makers. Rather, international and national efforts, including investments and policies, can primarily influence three factors: (1) dosage availability/rollout speed, (2) target vaccine coverage; and (3) the continuation or relaxation of control measures. Within this context, in Figure 4 we present the relative reduction in deaths for vaccine allocation prioritizing older adults as each of those factors is modified. Equivalent results for

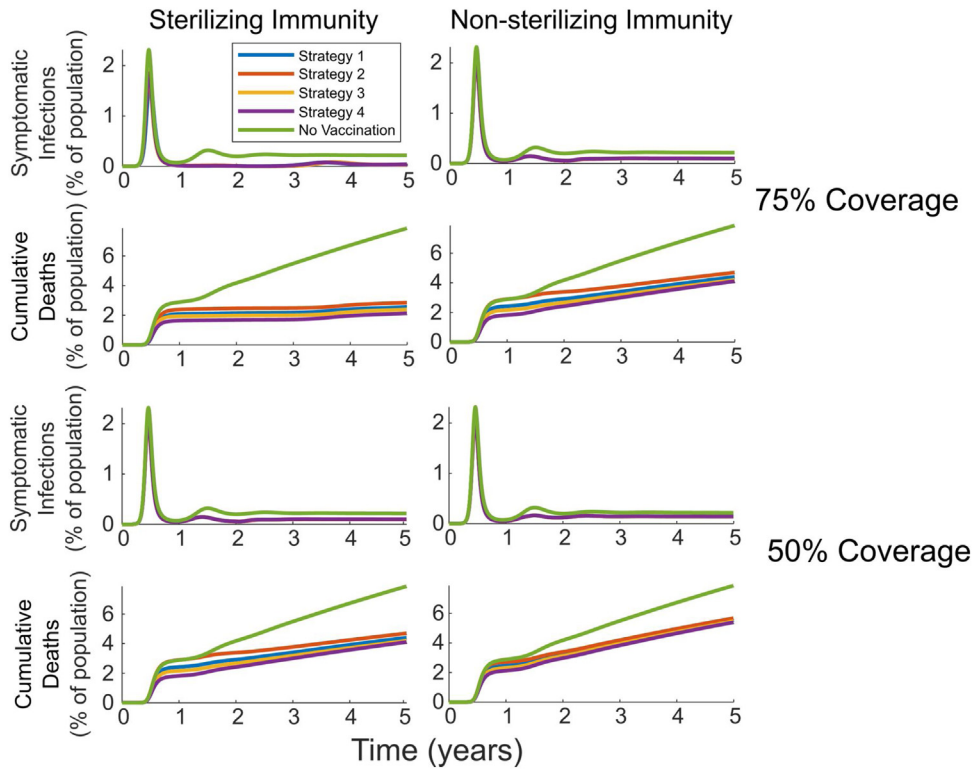

Figure 2. Simulated infection curves and cumulative deaths with four vaccination strategies.
Each simulation assumed that 3% of the population was vaccinated each month, with a vaccine efficacy of 75%, no control measures, and an R_0 of 2.4. Strategies 1–4 corresponds to no prioritization of any age group in vaccination, while strategies 2–4 correspond to prioritizing those 20–40, 40–60, and >60 years old respectively. Strategy 4 leads to the greatest reduction in deaths, though all strategies perform better than no vaccination.

strategies 1–3 are presented in the supplemental materials. Under low coverage, the speed at which the vaccine is rolled out has little effect on the overall reduction in deaths.

Discussion

Our findings support international recommendations to prioritize COVID-19 vaccine allocation for older adults (World Health Organization, 2020b), as it contributed to the greatest relative reduction in overall mortality in all scenarios considered. Our analyses indicate that prioritising younger populations will have a greater impact on reducing incidence of infections relative to prioritizing older age groups. However, these reductions are marginal and prioritizing younger age groups will contribute the lowest relative reduction on COVID-19 mortality compared to other strategies, including equal distribution to the general population. These findings were consistent, although to different degrees, across all model iterations, including COVID-19 vaccines that confer sterilizing and non-sterilizing immunity. A similar framework for equitable allocation of COVID-19 vaccine that prioritised older populations was adopted by the panel of experts from the Centers for Disease Control and Prevention (CDC), the National Institutes of Health (NIH) and the National Academies (Gayle et al., 2020).

The characteristics of first-generation COVID-19 vaccines remain a question of debate (Peiris and Leung, 2020). However, it is unlikely that the first vaccines will provide 100% protective efficacy nor protection from asymptomatic carriage. Most candidate vaccines that are currently in Phase III trials aim to assess efficacy against clinical disease (Peiris and Leung, 2020). Recent reports from leading COVID-19 vaccine candidates in advanced clinical development indicate vaccine efficacy against confirmed cases of >90%, including among older populations (Callaway, 2020). The WHO has indicated that a successful vaccine should be 50% efficacious (Krause et al., 2020). We observed greater differences between COVID-19 vaccine allocation strategies at higher vaccine efficacy values for relative reductions in deaths. Vaccines that confer sterilizing immunity also led to greater relative reductions of cases and deaths compared to vaccine that did not provide sterilizing immunity. This is likely attributable to the fact that sterilizing vaccines disrupt viral transmission of. However, COVID-19 vaccine challenge studies in primates demonstrated reductions in symptomatic disease and viral load, but did not produce sterilising immunity (Corbett et al., 2020; van Doremalen et al., 2020).

Policy makers around the world, especially those in low- and middle-income countries, have had to make difficult decisions related to the implementation and relaxation of lockdown measures. Lockdown measures help to reduce transmission of the virus but have been associated with several

secondary effects, including reduced livelihoods (Walker et al., 2020), increased morbidity and mortality due to limited utilization of routine health services (Roberton et al., 2020), and several psychosocial and mental health implications (Roy et al., 2020). Effective COVID-19 vaccines could alleviate the need for restrictive lockdown measures. Our model allowed us to make relative comparisons of COVID-19 vaccine allocation strategies in the context of various control measures. We found that the relative reduction in cases and deaths does not meaningfully change based on the level or absence of control measures when the vaccine does not provide sterilizing immunity. However, in the model where effective vaccines do provide sterilizing immunity, the relative

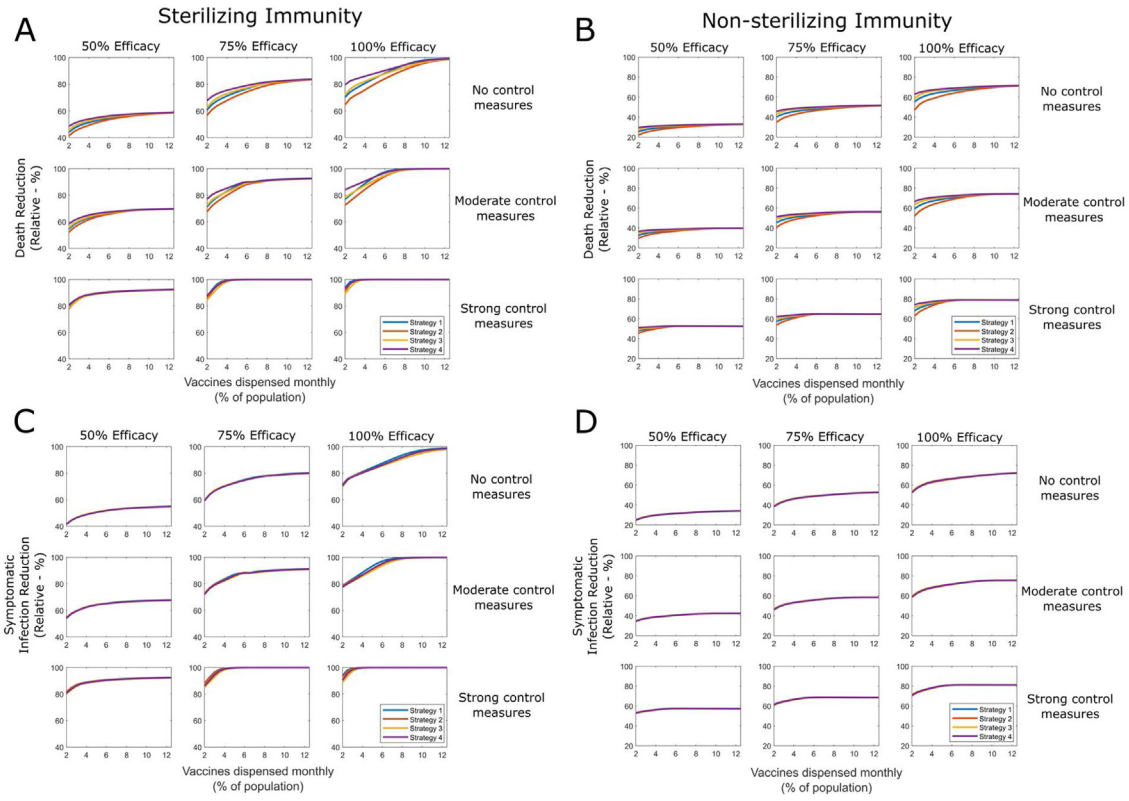

Figure 3. Comparison of benefit for four different vaccination strategies, against no vaccination.
The relative reduction in deaths (A, B) and symptomatic infections (C, D) over a 5-year period are presented for four vaccination strategies, under varying speeds of vaccine dispensation. Results are stratified using three different vaccine efficacies, three types of control measure policy, and assuming a vaccine grants either sterilizing or non-sterilizing immunity. All simulations assumed vaccination did not exceed a population coverage of 75% and used an R_0 of 2.4. Baseline deaths were calculated assuming no control measures and the same R0 value.

reduction in cases and deaths is substantially greater when strong control measures are in place.

In accordance with COVAX Facility requirements (World Health Organization, 2020a), the allocation of COVID-19 vaccines to health care workers and social workers should be prioritized. There remains an acute health workforce shortage in many parts of India (Rao et al., 2016; Shrivastava and Shrivastava, 2019). Immunizing this important population with priority, together with adequate supply of personal protective equipment, will help to strengthen the resiliency of the fragile health system during the epidemic. While health workers remain at higher risk of SARS-CoV-2 infection (Nguyen et al., 2020), there is insufficient evidence to determine how they contribute to transmission. Our model did not consider a health worker compartment.

India has a robust national immunization program for early childhood that has been strengthened recently with demonstrable gains in vaccination coverage (Gurnani et al., 2018). The recent introduction and rollout of the pneumococcal conjugate vaccine and rotavirus vaccine have shown that new vaccines can be successfully rolled out within existing public health infrastructure (Malik et al., 2019). While a clear strategy for childhood vaccination exists globally and in India, a blueprint for adult immunization is recognizably inadequate and is being increasingly acknowledged as important for sustaining and enhancing health outcomes (Privor-Dumm et al., 2020). So far, India has initiated the process of targeting adults by setting up of health centers adult and immunization as an example of a life course approach to health services (Lahariya and Bhardwaj, 2020).

During the influenza pandemic of 2009, the WHO Initiative was able to deploy almost 80 million doses of pandemic H1N1 vaccine to resource-limited settings in 77 poorest countries (World Health Organization, 2012). This experiences deploying vaccines in pandemic settings provide lessons that should be utilized to enhance current allocation vaccine plans. First, the availability of robust evidence of demographics, including at-risk population groups is critical for successful vaccine deployment. Simulations with varying scenarios, such the current report, can complement evidence and play an important role in allocation decisions. Second, coordinated planning of national vaccine deployment, including establishment of a robust supply chain management system, was crucial to effective utilization of scarce vaccine resources. Third, funding support from global agencies, local funders, and governments helped sustain vaccine rollout. Finally, public communication and clear messaging was essential to enhancing public confidence in vaccines. Due to data availability constraints, and evolving scientific understanding of COVID-19, the model makes a number of key assumptions about COVID-19 epidemiology and transmission dynamics. Age for confirmed cases and deaths were not available in publicly available data. We therefore used published data from India to inform age-specific dynamics and fatality. Infection was assumed to provide temporary immunity against reinfection for one year, with other values explored in the supplemental materials. The actual average length of immunity due to COVID-19 infection is not precisely known and likely varies based on infection severity (Randolph and Barreiro, 2020; van der Heide, 2020; Wajnberg et al., 2020). Many model parameters, such as force of infection, latent period, time to recovery, and vaccine efficacy all likely vary with age, and potentially with time. However, given lack of clear data, these factors were assumed constant. In addition, due to data availability,

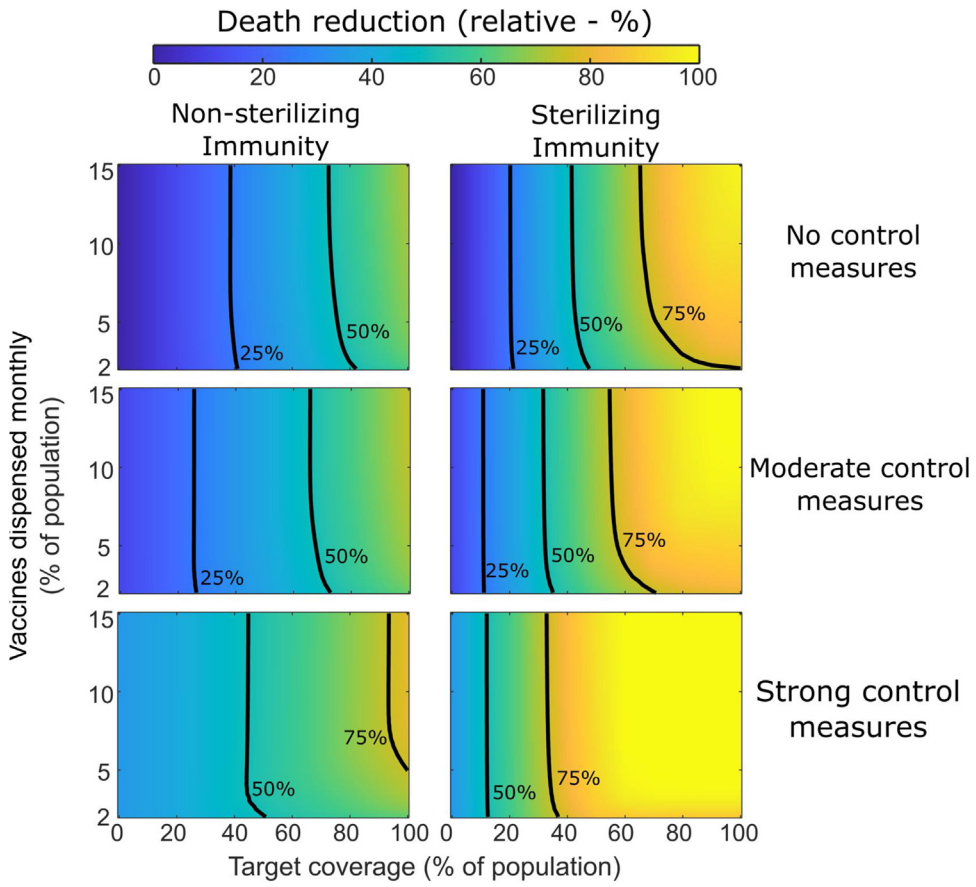

Figure 4. Relative reduction in deaths using vaccination strategy four.
Effectiveness of strategy 4 comparative to no vaccination and no control measures is given under varying dispensation speeds, and to different maximum population coverage levels, with and without control measures. Contour lines represent 25%, 50% and 75% reductions in cumulative deaths, comparative to no vaccination and no control measures. All simulations were performed using an R_0 of 2.4.

deaths were estimated using case fatality ratios and not infection fatality ratios, under the assumption that discrepancies between case and infection fatality ratios are predominantly due to undetected asymptomatic infections.

Within the model, vaccines were distributed to a target coverage level, which was constant for each age group. For practical implementation, certain age groups will likely be easier to reach and less reticent to vaccination than others, meaning true coverage may vary by age (Cobos Muñoz et al., 2015). Preliminary evidence suggests that COVID-19 may be subject to seasonal forcing (Sajadi et al., 2020). This was not accounted for in the model to lack of a clear timeline for when vaccine rollout would begin. Given current understanding of COVID-19 immunity dynamic, there will likely be some prevalence of infection-driven immunity that exists before vaccine rollout begins. However, given uncertainties associated with vaccine delivery timelines, expected seroprevalence estimates, and the quality and duration of immunity from natural infection, there is no reliable data to inform this within the model. As a result, no prior immunity within the population was assumed. More broadly, this model was designed for comparison between vaccination strategies, and is not meant provide exact estimates of cumulative deaths or symptomatic infections. Rather results are meant to represent the estimated relative benefit of different scenarios.

Conclusions

Progress towards development and approval of SARS-CoV-2 vaccines has been extraordinarily fast; however, challenges of fair and optimal allocation remain. Supply limitations and logistic challenges suggest that vaccine administration across India will be slow, necessitating distribution strategies that offer the greatest protection. We illustrate that when accounting for Indian population structure, vaccination of older age groups (>60 years) consistently provides the greatest reduction in cumulative deaths. Prioritized vaccination of younger age groups was often seen to reduce symptomatic infection, but this benefit was typically offset by larger case fatality in older populations. Prioritized vaccination of older populations was seen to be optimal regardless of vaccine efficacy, dispensation speed, force of infection, and target coverage, and independent of whether NPIs were implemented.

Conflict of interest

The authors report no conflicts of interest.

Sources of support

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Author contributions

CB conceptualized the project and collated the data. BF and BW developed the model and developed the code. BF prepared the visualizations. All authors contributed to the design of the model, the interpretation of the results, and the initial draft of the manuscript.

Ethical approvals

No human subjects were involved in this work and therefore ethical approvals were not required for the development of this manuscript.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ijid.2020.12.075.

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