Health Decision

ORIGINAL ARTICLE

Different vaccination strategies for preventing coronavirus disease 2019 in Kenya: A dynamic modelling study of health impact and cost-effectiveness

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ABSTRACT

Background: Vaccination can significantly reduce the health impact and economic burden of coronavirus disease 2019 (COVID-19), but vaccination levels for COVID-19 in most African countries lag far behind global averages. We assessed the cost-effectiveness of different COVID-19 vaccination strategies in Kenya and determined the optimal vaccination strategy. **Methods:** Using a dynamic transmission model, we divided the population into three groups: 0-18 years, 19-58 years and 58+ years. We assessed the effectiveness and cost-effectiveness of three vaccination strategies at different numbers of daily vaccinations based on previous studies and public databases. Nine scenarios were modeled and compared to no-continuation-vaccination to calculate the number of averted diseases, averted deaths, and net benefits of different vaccination strategies. One-way sensitivity analysis and probabilistic sensitivity analysis were conducted to assess the stability of our findings. **Results:** Compared to no-continuation-vaccination for various vaccination scenarios, all vaccination strategies were found to be effective and cost-saving. The incremental net benefit ranged from 0.235 billion USD to 2.305 billion USD, and prioritizing vaccination boosters for individuals aged 19-58 was identified as the most cost-effective option. On the other hand, prioritizing vaccination for the unvaccinated population aged 58 and above could potentially reduce COVID-19 related deaths by 1.59%-56.60%, which was the most effective approach in avoiding cause-specific deaths. However, all vaccination strategies were found to be ineffective in controlling the infection trend when compared to no intervention under different vaccination scenarios, with only 474,318-5,306,865 infections potentially being prevented. **Conclusion:** Timely and widespread vaccination against COVID-19 in Kenya is effective and cost-effective, a specific vaccination strategy should be selected based on decision-making needs. Priority vaccination for the elderly without vaccination may be more cost-effective compared with other vaccination strategies.

Key words: coronavirus disease 2019, vaccines, cost-effectiveness analysis, Kenya

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INTRODUCTION

Coronavirus disease 2019 (COVID-19) is a serious global public health problem that has spread to almost all countries around the world and caused devastating effects. As of November 2022, approximately 636 million people worldwide have been infected with COVID-19, including 6.6 million people died from it.[1] With such a severe outbreak of COVID-19 infection, many countries have effectively slowed the spread of COVID-19 and reduced COVID-19-related deaths by implementing preventive measures such as mask wearing, social distance maintenance, close contact tracing and vaccination.

In addition to the African continent, the vast majority of other regions have achieved more than 100 doses of vaccination per 100 people for the majority of the population.[1] The continent has experienced unprecedented health challenges since the first case of COVID-19 entered Algeria on 25 February 2020. The pandemic has lasted for over two years, and confirmed cases of COVID-19 were reported in all 47 African countries. The death rate from COVID-19 in Africa was higher due to poor sanitation, difficult adherence to preventive measures, and lack of vaccines.[2] Furthermore, in most African countries, only three kinds of people—travelers with symptoms of COVID-19, people in close contact with positive cases and residents of high prevalence areas—are likely to be tested for COVID-19. Thus, COVID-19 testing is infrequent, which potentially masks the true transmission of COVID-19 and related death cases.[3]

Southern and northern Africa have relatively high COVID-19 vaccination rates because of relative well-developed economy and other factors, while in Central and East Africa, vaccination rates are even less than 20 doses per 100 people. In Kenya, the country in East Africa, there were approximately 341,043 confirmed cases and 5684 deaths as of November 2022. As one of many low-income countries, Kenya started vaccinating frontline workers and people over 58 years old, and in the second half of the year for people over 18 years old with the help of the Covid-19 Vaccine Global Access Facility (COVAX) in May 2021.[4] However, there are currently only around 42 doses of vaccine per 100 people, and most of the vaccinated population is likely to face expiry or reduced effectiveness. As of May 2022, Kenya has received 32 million doses of vaccine.[5] Large-scale population vaccination will be proposed, but no studies have yet examined the effectiveness and cost-effectiveness of a limited vaccination schedule in Kenya while the new coronavirus variant vaccine is still effective. The Kenyan government is unable to make quick and rational decisions about whether to prioritize booster vaccination or to prioritize coverage of the uncovered population, knowing that any wrong choice will exacerbate the spread of COVID-19. In this study, we conducted an effectiveness and cost-effectiveness assessment to address this issue.

METHODS

Study design

According to the Kenyan vaccination policy, we divided three age groups: 0-18, 19-58 and 58+ years, and based on a dynamic transmission model constructed in Microsoft Excel 2019, we conducted simulations to assess the effectiveness and cost-effectiveness of different COVID-19 vaccination strategies. We reported these economic evaluations according to Consolidated Health Economic Evaluation Reporting Standards (CHEERS) statement.[6]

Data sources

The parameters used for the study were taken from published literature or public databases, as well as World Health Organization (WHO) statistics, *etc.* Parameters, such as infection rate, vaccination status, costs and utilities, were parametrized for the age groups classified.

This cost-effectiveness analysis was conducted from a health system perspective. In terms of costs, we considered the cost of vaccines and direct medical costs, with the cost of vaccines including the cost of vaccination, transportation and preservation in addition to the vaccine itself, all expressed in 2021 dollars.

The probabilities of infection used in this model were derived from differential equation calculations, progression rates after infection were from published literature, and age-specific background mortality rates were from Kenyan Ministry of Health statistics (Table 1-3).

Model structure

As shown in Figure 1, we constructed a dynamic transmission model to simulate health progression in three age groups: 0-18, 19-58 and 58+ years based on publicly available data. Since most of the COVID-19 vaccine protection period is about six months,[35] the model was simulated for 180 days with the cycle length of one day.

Due to the low detection rate in Kenya, it is likely that a large number of asymptomatic and mildly infected individuals were not detected, and the actual number of infections would be much greater than the WHO statistics. To determine the initial cohort, we determined the actual number of possible infections based on detection rates and WHO statistics.[3] We identified the probability of infection based on the number of effective exposures, mask-wearing and vaccination status for different age groups, the specific transfer probability was calculated as shown in Figure 1. As it might be difficult to meet WHO standards for hand washing in Africa, we did not consider the impact of this protective measure.[36] As the majority of Kenyan vaccinees were vaccinated early (the vast majority more than six months ago), we considered the protective effect of all vaccinated populations, except those who received the booster dose, to be equivalent to those who received one dose of vaccine.[35] We supposed that treatment would retard disease progression and assumed this probability of the retardation. Natural mortality rates for all age groups were applied to the cohort, and it was assumed that only patients with severe and critical illnesses were likely to die.

Table 1: Parameters of the initial cohort

Parameter	Base-case value	Deterministic range	PSA distribution	Source
Total population				KNBS [7]
0-18 years old	22,855,913	-	-	
19-58 years old	21,747,690	-	-	
58+ years old	2,960,693	-	-	
Total number of recoveries	334,920	-	-	WHO [1]
Proportion of recovery with antibody	20.00%	10.00%-30.00%	Beta	Wamalwa *et al.*[8]
The number of people vaccinated with at least one dose	13,969,231	-	-	WHO [1]
The number of people vaccinated with booster dose	1,568,659	-	-	
The number of people infected at the initial stage of simulation	700	-	-	
The proportion of people having tested with COVID-19	10.50%	5.00%-15.00%	Beta	Manguro *et al.*[9]
The proportion of infection with symptoms	75.00%	60.00%-90.00%	Beta	Du *et al.*[10]

COVID-19: coronavirus disease 2019; WHO: World Health Organization; KNBS: Kenya National Bureau of Statistics; PSA: probabilistic sensitivity analysis.

Table 2: Model parameters

Parameter	Base-case value	Deterministic range	PSA distribution	Source
Natural mortality/year				GBD [11]
Age category (years)				
0-18	0.28%	0.23%-0.33%	Beta	
19-58	0.71%	0.61%-0.82%	Beta	
58+	12.52%	11.55%-13.59%	Beta	
Relative rate of contact (compared to 19-58 years old)				Zhao *et al.*[12]
Age category (years)				
0-18	77.14%	69.43%-84.86%	Beta	
19-58	100.00%	-	-	
58+	51.43%	46.29%-56.57%	Beta	
Number of daily contacts (γ)				Dobreva *et al.*[13]
0-18 years old				
Age category (years)				
0-18	1.71	1.54-1.89	Gamma	
19-58	9.43	8.49-10.37	Gamma	
58+	0.43	0.39-0.47	Gamma	
19-58 years old				
Age category (years)				
0-18	9.43	8.49-10.37	Gamma	
19-58	4.29	3.86-4.71	Gamma	
58+	1.29	1.16-1.41	Gamma	
58+ years old				
Age category (years)				
0-18	0.43	0.39-0.47	Gamma	
19-58	1.29	1.16-1.41	Gamma	
58+	6.00	5.40-6.60	Gamma	
The proportion of effective contact (δ)	30.00%	27.00%-33.00%	Beta	Assumed
Proportion of mask wearing(ε)				Nwaeze *et al.*[14]
Age category (years)				
0-18	72.00%	64.80%-79.20%	Beta	
19-58	34.00%	30.60%-37.40%	Beta	
58+	19.00%	17.10%-20.90%	Beta	
Effectiveness of interventions				

Mask wearing (ζ)	50.00%	45.00%-55.00%	Beta	Ueki *et al.*[15]
Ratio of protection rate of one dose of vaccine to that of two doses	27.54%	24.79%-30.29%	Beta	Whitaker *et al.*[16]
Ratio of protection rate of booster dose of vaccine to that of two doses	100.00%	90.00%-100.00%	Beta	Chenchula *et al.*[17]
Protection rate of two doses AZD vaccines				
Against infection (ι2)	50.70%	45.63%-55.77%	Beta	Siqueira *et al.*[18]
Against symptom (λ2)	73.70%	65.10%-80.10%	Beta	Falsey *et al.*[19]
Against severe (υ2)	94.20%	53.30%-99.30%	Beta	
Protection rate of one dose AZD vaccines				Whitaker *et al.*[16]
Against infection (ι1)	13.96%	-	Beta	
Against symptom (λ1)	20.30%	-	Beta	
Against severe (υ1)	25.94%	-	Beta	
Protection rate of booster dose AZD vaccines				Chenchula *et al.*[17]
Against infection (ιb)	50.19%	-	Beta	
Against symptom (λb)	72.96%	-	Beta	
Against severe (υb)	93.26%	-	Beta	
Infection rate of patients exposed to symptomatic infection (β_3)	6.40%	5.76%-7.04%	Beta	Thron *et al.*[20]
Relative infectiousness of asymptomatic individual	50.00%	45.00%-55.00%	Beta	McEvoy *et al.*[21]
Relative infectiousness of isolation individual (θ)	66.00%	59.40%-72.60%	Beta	Thron *et al.*[20]
Infection rate of patients exposed to asymptomatic infection (β_2)	3.20%	-	Beta	McEvoy *et al.*[21]
Infection rate of patients exposed to infections latent (β_1)	15.00%	13.50%-16.50%	Beta	Aleta *et al.*[22]
Recovery time (days)				
Latency (t1)	5.20	4.68-5.72	Gamma	Kim *et al.*[23]
Asymptomatic (t2)	3.50	3.15-3.85	Gamma	Choi *et al.*[24]
Mild or moderate (t3)	7.00	6.30-7.70	Gamma	Orangi *et al.*[25]
Severe (t4)	12.00	10.80-13.20	Gamma	
Critical (t5)	20.00	18.00-22.00	Gamma	
Mortality rate for severe or critical illness				
Age category (years)				
0-18	0.00%	0.00%-0.05%	Beta	Marois *et al.*[26]
19-58	0.00%	0.01%-1.28%	Beta	
58+	0.07%	1.11%-13.30%	Beta	
Test and treatment rate				
Asymptomatic (ν1)	59.86%	30.00%-50.00%	Beta	Kiarie *et al.*[27]
Mild or moderate (ν2)	59.86%	30.00%-50.00%	Beta	
The rate of test for severe or critical people (μ)	40.00%	20.00%-60.00%	Beta	Assumed
Severe (ν3)	80.00%	70.00%-90.00%	Beta	
Critical (ν4)	80.00%	70.00%-90.00%	Beta	
PCR test				Reddy *et al.*[28]
Sensitivity	70.00%	50.00%-90.00%		
Specificity	100.00%	-	-	
Disease progress rate				
Mild or moderate→Severe (τ1)	1.95%	1.76%-2.15%	Beta	Fu *et al.*[29]
Severe→Critical (τ2)	3.29%	2.96%-3.61%	Beta	
Treatment delays progress (ω)	80.00%	72.00%-88.00%	Beta	Assumed

PSA: probabilistic sensitivity analysis; GBD: Global Burden of Disease.

Table 3: Cost and utility

Parameter	Base-case value	Deterministic range	PSA distribution	Source
Cost of test and prevention (USD)				
Mask/day	0.14	0.13-0.15	Gamma	Mukerji *et al.*[30]

PCR test	26.00	13.00-52.00	Gamma	Gavi [31]
Vaccine/dose	3.00	-	-	
Syringes and safety boxes/dose	0.04	0.04-0.04	Gamma	Pearson *et al.*[32]
Cold chain costs/dose	0.13	0.12-0.15	Gamma	
Human resource/dose	0.03	0.03-0.03	Gamma	
Transport/dose	0.38	0.34-0.42	Gamma	
Wastage	15.00%	13.50%-16.50%	Beta	
Cost of treatment (USD)/day				Barasa *et al.*[33]
Asymptomatic	19.75	17.78-21.73	Gamma	
Mild or moderate	19.75	17.78-21.73	Gamma	
Severe	129.45	116.51-142.40	Gamma	
Critical	623.14	560.83-685.45	Gamma	
Health utilities				
Susceptible person	0.95	0.90-0.99	Beta	Alinia *et al.*[34]
Latency	0.95	0.90-0.99	Beta	Assumed
Asymptomatic	0.95	0.90-0.99	Beta	
Mild or moderate	0.85	0.80-0.89	Beta	Alinia *et al.*[34]
Severe	0.77	0.73-0.80	Beta	
Critical	0.63	0.60-0.66	Beta	
Recovery	0.90	0.85-0.94	Beta	
Death	0.00	-	Beta	

PSA: probabilistic sensitivity analysis.

We compared the effectiveness and cost-effectiveness of various vaccination strategies to those of no-continuation-vaccination, using indicators such as the number of infections averted, number of symptomatic infections averted, number of severe infections averted, number of deaths averted due to COVID-19 infection, additional QALY gained and Incremental net benefit (INB).

Vaccination strategies and scenarios

Although many types of vaccines were obtained in Kenya with the help of many countries and Gavi (Beijing CNBG-BBIBP-CorV, Pfizer BioNtech-Comirnaty, Moderna-Spikevax, Janssen-AD26. COV2-S, SII-Covishield),[1] the majority of vaccines initially procured and administered were the Oxford/Astra Zeneca vaccine *via* COVAX,[37] so we assumed that the effectiveness of subsequent vaccination was consistent with the Oxford/Astra Zeneca vaccine.

We considered three separate vaccination strategies, with strategy 1 prioritizing up to 2 doses for unvaccinated people aged 58+ years, then for those aged 18-58 years and finally for those aged 0-18 years; strategy 2 prioritizing booster doses for vaccinated people aged 18-58 years, then for vaccinated people aged 58+ years, then for those aged 0-18 years; and strategy 3 prioritizing up to 2 doses for unvaccinated people aged 18-58 years, then for those aged 58+ years, and finally for those aged 0-18 years.

Due to the uncertainty of vaccination mobilisation capacity in Kenya, we assumed vaccination scenarios of 30,000, 50,000 and 100,000 doses per day. In total, nine scenarios were simulated in the model by combining three vaccination strategies.

Effectiveness and cost-effectiveness analysis

In comparison to no-vaccination, we calculated the potential disease incidence and deaths avoided by different vaccination strategies. Meanwhile, we combined the additional vaccine costs required with the total cost input difference to determine the effectiveness and cost-effectiveness of strategies, prioritizing the cost-effectiveness of the vaccination strategies in terms of the incremental net benefit (ΔUtility*WTP-ΔCost). Based on WHO recommendations,[38] three times Kenya's GDP per capital in 2021 (6657 USD) were chosen as the willingness-to-pay threshold.

Sensitivity analysis

We performed the one-way sensitivity analysis to identify the parameters that had largest impacts on the results. For probabilistic sensitivity analysis, we conducted to 1000 Monte Carlo simulations to verify the results' stability with different combinations of all parameters.

RESULTS

Base-case analysis

Simulation results have shown that if COVID-19

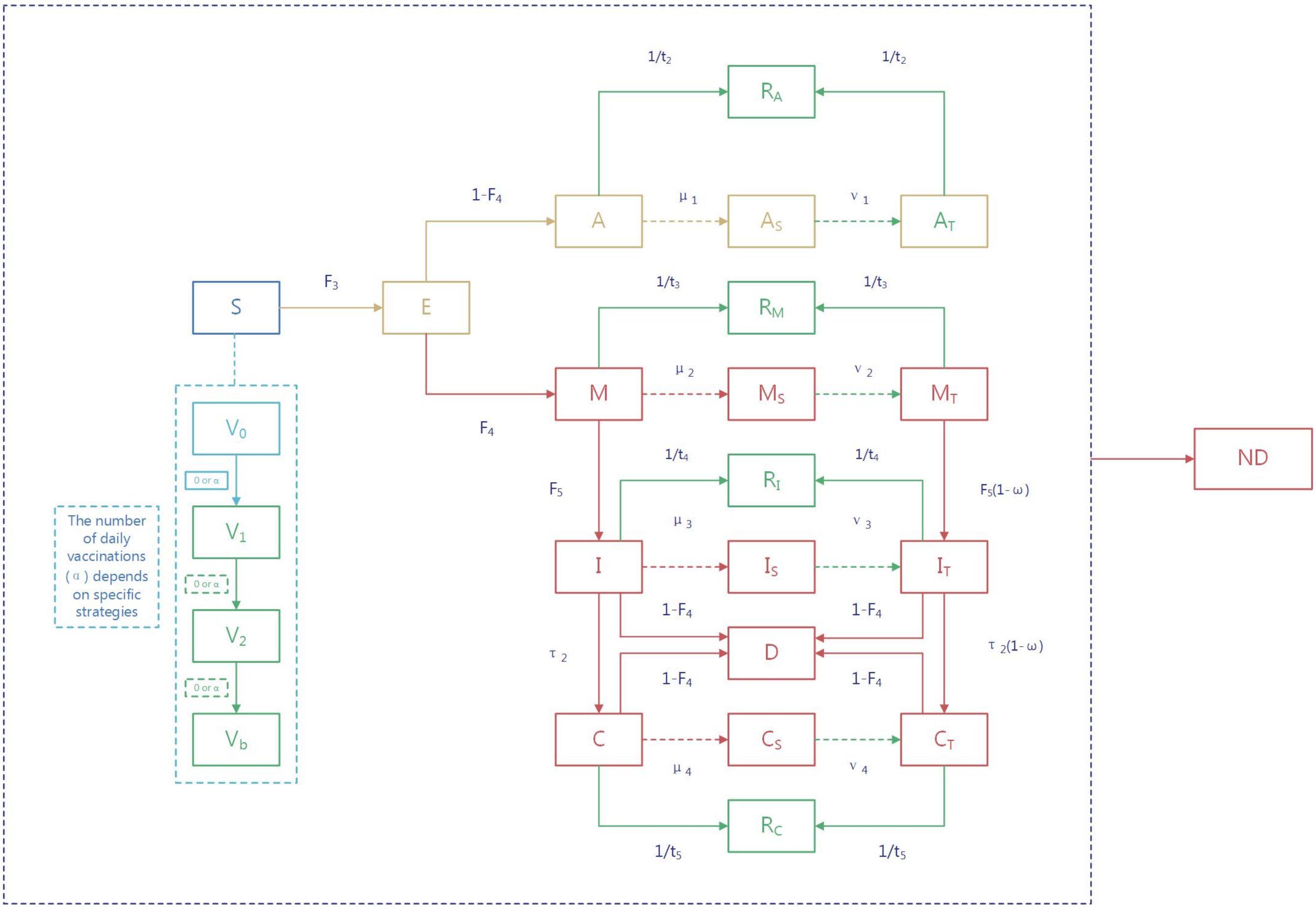

Figure 1. COVID-19 Dynamic Infection Model for Kenya. S: susceptible; V_0: unvaccinated susceptible; V_1: 1-dose vaccinated susceptible; V_2: 2-dose vaccinated susceptible; V_b: booster vaccinated susceptible; E: incubation period; A: asymptomatic; A_S: detected asymptomatic; A_T: treated asymptomatic; R_A: recovered asymptomatic; M: mild to moderate symptomatic infected; M_S: detected symptomatic infected; M_T: treated symptomatic infected; R_M: recovered mild to moderate symptomatic infected; I: severe infected; I_S: detected severe infected; I_T: treated severe infected; R_I: recovered severe infected; C: critically infected; C_S: detected critically infected; C_T: treated critically infected; R_C: recovered critically infected; D: died from COVID infection; ND: died of natural causes; COVID-19: coronavirus disease 2019.

vaccination efforts would not be continued, over the next six months, more than 40 million people in Kenya could become infected. Of these cases, over 35 million individuals would exhibit symptoms, with more than 0.6 million people experiencing critical illness, and resulting in 2000 deaths.

As shown in Table 4, all vaccination strategies, compared with no-continuation-vaccination, were effective and cost-effective.

As depicted in Figure 2, all vaccination strategies were found to be ineffective in controlling the trend of infection when compared to no intervention across different vaccination scenarios, with only 474,318-5,306,865 potential infections being preventable.

However, as shown in Figure 3, although vaccination had a limited effect in preventing infection compared to non-vaccination, it could reduce the infected cases, symptomatic infections and severe illnesses, and could prevent up to 50% or more of deaths caused by COVID-19.

Comparison of the effectiveness and cost-effectiveness of different vaccination strategies showed that changes of daily vaccinated cases did not significantly affect the conclusions, with the highest number of infections, symptomatic and severe illnesses avoided by vaccination strategy 2, *i.e.,* prioritizing booster shots for people aged 19-58 years. Most related deaths could be avoided by vaccination strategy 3, *i.e.,* prioritizing vaccination for unvaccinated older people aged 58+ years. Difference in effectiveness between the different strategies, particularly the avoided death cases, decreased as the daily vaccinated cases increased.

All of the vaccination strategies were found to be cost-saving, with a range of 204.10 USD to 1987.12 million USD in cost savings compared to no-continuation-vaccination. The incremental net benefit of these vaccination strategies was in the range of 0.235 USD to 2.305 billion USD. The most cost-effective strategy was Vaccination strategy 2, which prioritized booster vaccination for individuals aged 19-58 years.

Table 4: Results of base-case

Strategy		Cost of vaccination (USD)	Cost of mask wearing (USD)	Cost of test (USD)	Cost of treatment (USD)	Total cost (USD)	Effectiveness (QALYs)	Incremental net benefit (USD)	ICER(USD/QALY)
	No. vaccination	0.00	263,085,559.69	738,189,736.00	16,538,150,996.18	17,276,340,732.19	7,835,838,808.32	-	-
30,000 people are vaccinated every day	Vaccination strategy i	22,244,220.00	264,567,180.35	730,149,573.90	16,313,572,726.13	17,065,966,520.03	7,837,905,385.55	248,065,183.77	-37,156.41
	Vaccination strategy ii	22,244,220.00	268,123,984.16	722,741,898.22	15,942,829,603.31	16,687,789,721.53	7,8,40,900,676.70	680,871,169.18	-35,658.49
	Vaccination strategy iii	22,244,220.00	265,107,796.03	734,726,578.65	1,6,3,15,265,101.51	17,072,235,900.16	7,837,545,976.80	235,240,778.92	-39,000.30
50,000 people are vaccinated every day	Vaccination strategy i	37,073,700.00	266,158,056.17	722,646,728.42	16,107,025,058.76	16,866,745,487.18	7,840,031,421.99	486,061,626.40	-42,439.10
	Vaccination strategy ii	32,391,653.64	272,681,604.16	713,407,087.78	15,497,122,064.35	16,242,894,805.76	7,844,733,092.51	1,195,663,049.31	-42,410.13
	Vaccination strategy iii	37,073,700.00	266,501,854.15	732,132,958.93	16,161,399,039.38	16,930,605,698.31	7,838,725,079.85	398,375,882.20	-41,559.26
100,000 people are vaccinated every day	Vaccination strategy i	68,974,071.02	269,620,292.29	712,018,497.09	15,671,852,443.89	16,452,845,012.00	7,843,545,823.65	964,059,010.82	-43,638.50
	Vaccination strategy ii	50,912,278.87	283,814,204.38	695,080,032.00	14,543,254,098.13	15,289,220,409.00	7,853,290,968.79	2,305,419,041.68	-43,721.90
	Vaccination strategy iii	74,147,400.00	270,438,630.02	723,563,456.03	15,719,514,186.01	16,517,225,042.03	7,842,107,582.21	873,447,821.17	-44,199.59

QALY: quality-adjusted life year; ICER: incremental cost-effectiveness ratio.

Sensitivity analysis

We conducted a one-way sensitivity analysis for all parameters and found that most of the parameters' fluctuations did not affect the results, and that vaccination strategy 1 was likely to be the most cost-effective choice, only when the utility of the susceptible population was taken to a lower value or the utility of the recovered population was taken to an upper value.

As shown in Figure 4, the results of the probabilistic sensitivity analysis showed that when the willingness-to-pay threshold was taken to be one-time Kenya's GDP per capital in 2021, vaccination strategy 2 was the dominant choice for any vaccination scenario.

DISCUSSION

There is no doubt that New Coronavirus vaccination is necessary and ongoing all around the world, and COVID-19 is a great threat to refugees in Africa who live in overcrowded conditions and lack effective sanitation measures.[39] Due to challenges such as limited funding, concerns about the safety and uncertainty of the vaccines, and difficulties in vaccine storage and regulatory implementation,[40] vaccination had been delayed in most African countries compared to other regions, and current levels of vaccination lag significantly behind global averages.[1] Although New Coronavirus vaccination was introduced in Kenya as early as May 2021, as in most African countries, vaccination levels are lagging behind and many vaccinated populations require booster shots to maintain vaccine protection. In Kenya and many other low-income countries, vaccination sequencing remains to be addressed.

Our simulations showed that the most effective strategy was to prioritize booster doses for vaccinated individuals aged 18-58 years, followed by those aged 58+ years, and then those aged 0-18 years. In the base-case analysis, this strategy had the highest incremental net benefit compared to all other strategies, regardless of the daily vaccination dose.

To the best of our knowledge, our study is the first to address the issue of vaccination sequencing in a country with low-level vaccination such as Kenya. Our results showed that vaccination against COVID-19 was effective and cost-effective in Kenya at any vaccination scenario.

Main findings

All vaccination strategies resulted in cost savings ranging from 204.10 USD to 1987.12 USD million compared to no-continuation-vaccination, with an incremental net benefit of 0.235-2.305 billion USD. Prioritizing vaccination boosters for the 19-58 years old was found to be the most cost-effective option. Prioritizing vaccination for the unvaccinated 58+ population was found to be effective in avoiding cause-specific deaths, with potential to prevent 1.59%-56.60% of deaths due to COVID-19 infection. However, all vaccination strategies were not effective in curbing the trend of infection

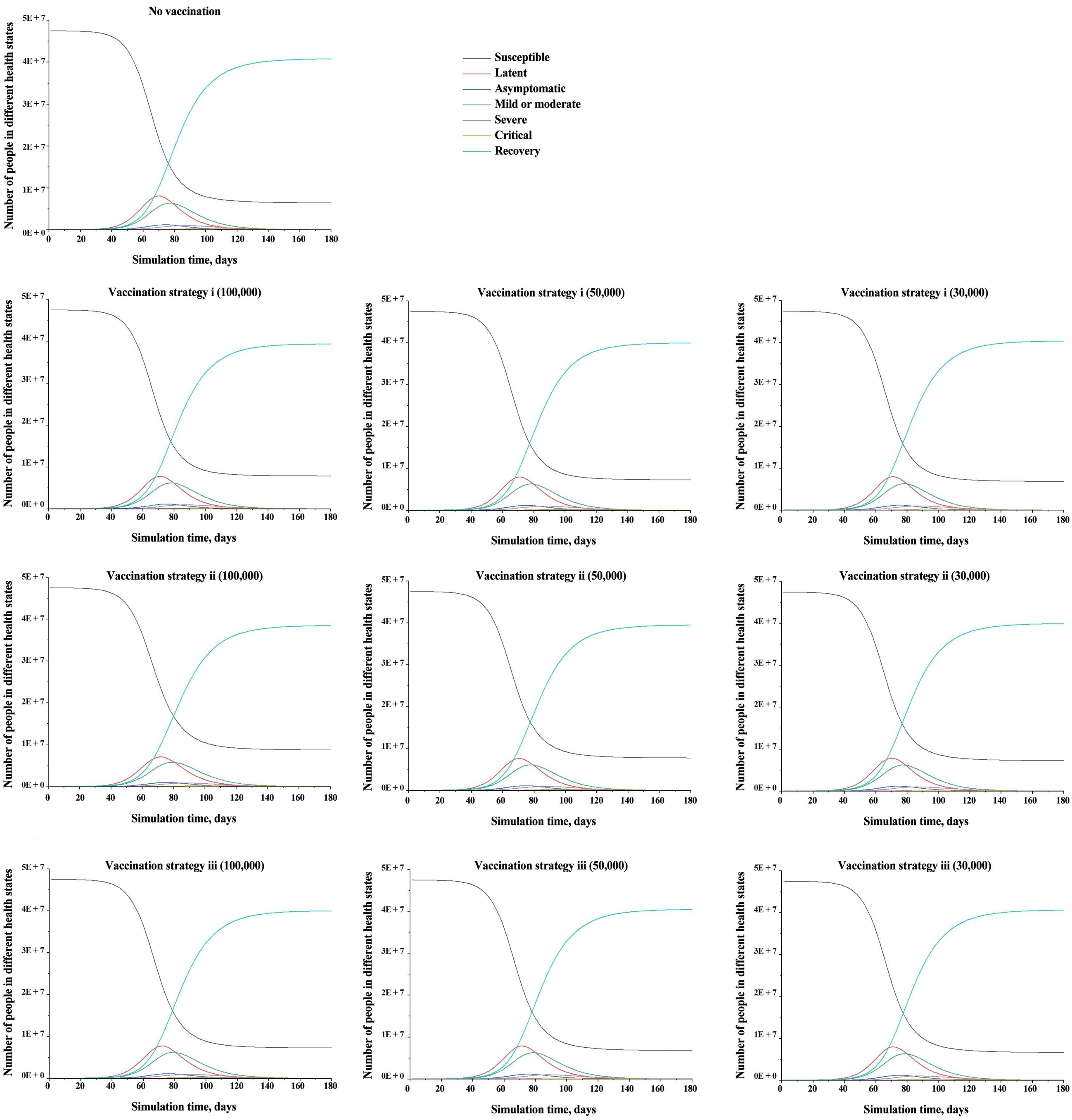

Figure 2. Number of people in each health state under different vaccination strategies.

compared to no intervention, and the number of avoided infections ranged from 474,318 to 5,306,865, depending on the vaccination scenario.

Based on the results of our research, we found the following points: Firstly, vaccination was unlikely to completely curb the trend of COVID-19, although it may reduce the infection cases, the number of symptomatic infections and severe diseases. Due to some factors—the high rate of COVID-19 infection, the difficulty in achieving high number of daily vaccination in most African countries, the overcrowded living and the lack of preventive measures such as mask-wearing and hand-washing,[14,36] COVID-19 transmission trends remain high in most African countries. Meanwhile, due to the current low detection rates and the lack of a robust reporting system in Kenya, the actual number of infections may be greatly underestimated.[9,41] Many asymptomatic or mild to moderate infections may not be diagnosed and, in addition, people with severe and critical infections may not receive effective treatment because the infrastructure and staffing for treatment is

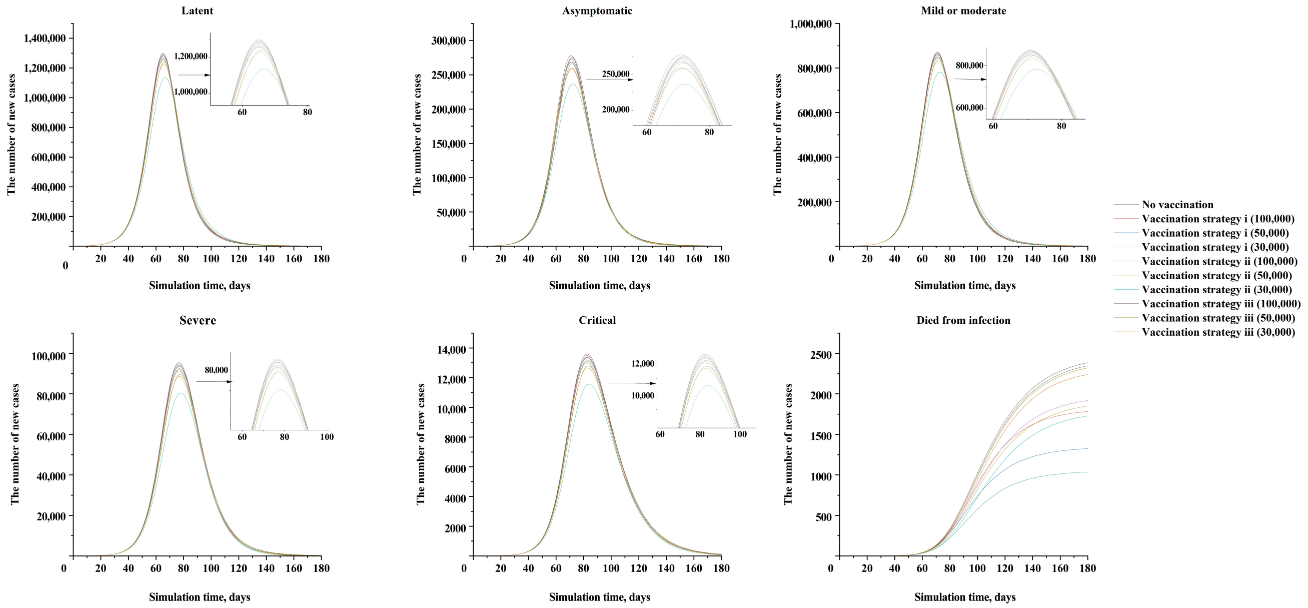

Figure 3. Addition cases in different health statuses under each vaccination strategy.

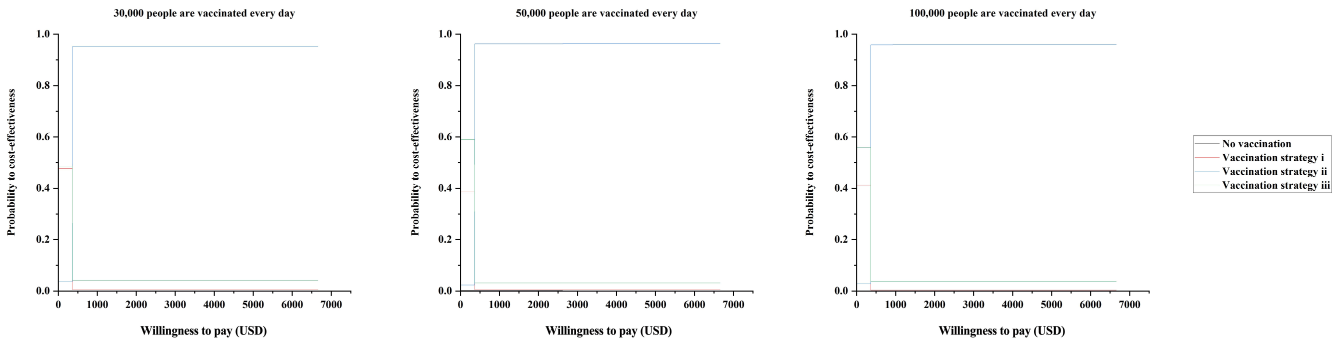

Figure 4. Cost-effectiveness acceptability curves for different vaccination strategies.

not adequate.[42]

Secondly, we found that all vaccination strategies were effective and cost-effective across all vaccination scenarios, and sensitivity analyses showed stability of the conclusions. Despite the additional costs of vaccination, vaccine transport, storage, administration and personnel, the price of the COVID-19 vaccine is quite affordable in comparison to other treatments, though we assumed relatively low uptake rates based on health service availability.

Finally, we found that prioritizing booster vaccination for people aged 19-58 years avoided the largest infection cases and was the most cost-effective. Based on sociological surveys, 19-58 years old people were found that they have more unprotected close contact and are at greater risk of COVID-19 infection compared to those aged 0-18 and 58+ years due to work *etc*.,[12] and the booster vaccination provides additional protection compared to one-dose vaccination. Thus, our conclusion is justified. The mortality rate from infection in the younger age group is much lower than in the older age group, so prioritizing vaccination of the population in the 58+ age group could avoid up to 50% deaths from COVID-19.[26]

Strength and limitations

Though it is the first study to explore vaccination prioritization and the necessity of booster shots in low-income countries, our results are robust and can be generalized to other low-income countries with low vaccination coverage rates for COVID-19 or those facing priority decisions about whether to give booster shots or cover the non-vaccination population. While the use of willingness-to-pay thresholds may be controversial, there is no doubt that vaccination is cost-saving. Most low-income countries have low GDPs, but even if the willingness-to-pay threshold is reduced to zero in the long term, these countries should choose strategy of timely and widespread vaccination against COVID-19 with the assistance of COVAX.

Although our study is well designed and generalizable, there are inevitable limitations. Firstly, we did not consider the actual health conditions and feasibility of vaccination in Kenya, although different daily vaccination cases were set to reduce this uncertainty. Most countries south of the Sahara, however, suffer from a severe shortage of healthcare workers and infrastructure, with only 0.2 doctors for 1000 inhabitants.[42] It is difficult to consider whether 30,000 people per day can be vaccinated in places such as refugee camps in Kenya, whether refrigerated stockpiles are sufficient to store vaccines, and whether transportation is sufficient to supply vaccines. Secondly, some parameters were taken from other low- and middle-income countries and adjusted to the Kenyan context. Finally, due to the limited parameters, we did not explore more detailed vaccination strategies, but only explored a limited sequence of vaccination in three age groups, without consideration in factors such as occupation.

CONCLUSION

Vaccination against COVID-19 in Kenya is an effective and cost-effective strategy, widespread vaccination is the recommended measure to reduce the disease and economic burden of COVID-19 in Kenya. Priority vaccination for the elderly without vaccination may be more cost-effective compared with other vaccination strategies.

DECLARATIONS

Author contributions

Tang W and Malone DC designed the study and interpreted findings. Zhou D and Shao H wrote initial drafts of the manuscript, developed the model and did all model analyses. Shao H and Tu Y search the parameters and data for the model. Zhou D and Shao T analysed the epidemic data to parameterise the model. Zhou D visualised the data. Malone DC, Xing Y and Tang W revised and polished the initial drafts. All authors reviewed the manuscript. All authors had full access to all the data in the study and the corresponding author had final responsibility for the decision to submit for publication.

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Ethics approval and consent to participate

Ethics approval was not required for this modelling study, as no patient-related individual data were used.

Conflict of interest

Daniel C. Malone is the Co-Editor-in-Chief of the journal. Wenxi Tang and Taihang Shao are the editors of the journal. The article was subject to the journal's standard procedures, with peer review handled independently of this member and his research group.

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