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Cost-Effectiveness Analysis of Strategies of COVID-19 Vaccination in Colombia: Comparison of High-Risk Prioritization and No Prioritization Strategies With the Absence of a Vaccination Plan

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ABSTRACT

Objectives: Our study compares two national COVID-19 vaccination plan strategies—high-risk prioritization and no prioritization—and estimates their cost-effectiveness compared with no vaccination, to generate possible recommendations for future vaccination plans.

Methods: We developed a Markov discrete-time, compartmental, deterministic model stratified by Colombian departments, healthcare workers, comorbidities, and age groups and calibrated to seroprevalence, cases, and deaths. The model simulates three scenarios: no vaccination, no prioritization of vaccination, and prioritization of high-risk population. The study presents the perspective of the health system of Colombia, including the direct health costs financed by the government and the direct health outcomes related to the infection. We measured symptomatic cases, deaths, and costs for each of the three scenarios from the start of the vaccination rollout to February 20, 2023.

Results: Both for the base-case and across multiple sensitivity analyses, the high-risk prioritization proves to be the most cost-effective of the considered strategies. An increment of US$255 million results in an incremental cost-effectiveness ratio of US$3339 per disability-adjusted life-year avoided. The simulations show that prioritization of high-risk population reduces symptomatic cases by 3.4% and deaths by 20.1% compared with no vaccination. The no-prioritization strategy is still cost-effective, with an incremental cost-effectiveness ratio of US$5223.66, but the sensitivity analysis the show potential risks of losing cost-effectiveness under the cost-effectiveness threshold (one gross domestic product per averted disability-adjusted life-year).

Conclusions: The high-risk prioritization strategy is consistently more cost-effective than the no-prioritization strategy across multiple scenarios. High-risk prioritization is the recommended strategy in low-resource settings to reduce the burden of disease.

Keywords: Colombia, cost-effectiveness, modeling, severe acute respiratory syndrome coronavirus 2, vaccination.

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Introduction

Since the start of the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) pandemic in Wuhan, China, in late 2019, the resulting disease, COVID-19, has caused at least 3.5 million deaths worldwide by May 30, 2021.[1] To halt the spread of the pandemic, several control strategies have been implemented, including nonpharmacological interventions and vaccination to prevent symptomatic infections and severe disease.[2,3]

Several vaccines have been approved for COVID-19, with efficacy in preventing symptomatic and severe COVID-19 ranging between 72% and 96%.[4-8] The indirect effects of vaccination, or herd immunity, could curtail the disease and prevent transmission through depletion of the susceptible population.[2,9]

The COVID-19 pandemic has reduced the growth of per-capita gross domestic product (GDP) by 6.2% worldwide,[10] increasing unemployment in most countries and, overall, having a disruptive effect on the economy. COVID-19 vaccination of the majority of the population would curtail transmission in settings with high vaccination coverage, allowing the economy to return to prepandemic levels. This means the social and economic benefits of COVID-19 vaccination in society would be substantial. Most high-income countries have reported high COVID-19 vaccination coverage. By May 31, 2021, countries such as Qatar, the United

Arab Emirates, the United States, and Iceland had exceeded the threshold of 70% of people having received at least one dose, allowing them to return to prepandemic societal dynamics. Despite this, the evidence is limited on vaccination strategies that would allow low- and middle-income economies to return to prepandemic dynamics in less time. Most nonhigh-income countries are prioritizing the population with the highest risk of COVID-19 mortality. Colombia, a middle-income country, has endured 87 747 deaths by May 30, 2021, and has already prioritized the vaccination of medical health personnel, adults older than 60 years, and people with comorbidities. It is expected that vaccination of a total of 35 million residents among the Colombian population (100% of individuals aged ≥ 16 years) will be achieved by late 2021 according to the Colombian Ministry of Health.[10]

To provide decision makers with evidence on the best strategies to optimize vaccines and economic resources, we designed and fitted a mathematical model to assess the cost-effectiveness of COVID-19 vaccination in Colombia, a middle-income country, through the perspective of Colombia's healthcare system. Our model compares two different vaccination strategies, high-risk prioritization and no prioritization, and measures their results against a no-vaccination scenario. The scenarios of this model could potentially inform COVID-19 vaccination in countries with similar health profiles worldwide and create more efficient vaccination policies. This study aims to answer the question of which vaccination strategy is best for the population resident in Colombia between a high-risk prioritization strategy and a no-prioritization strategy, both between mid-April 2021 and mid-February 2022, compared with a no-vaccination scenario, measuring the outcomes up to February 2023.

Methods

We developed a Markov discrete-time compartmental, deterministic model to identify the scenarios that would optimize the epidemiological and economic benefits of COVID-19 vaccination in Colombia. The model is fitted to the Colombian dynamics of SARS-CoV-2, stratifying all the population resident in Colombia by geopolitical departments, decennial age groups (< 10, 10-19, …, 60-69, 70+ years), high-risk occupations (ie, healthcare workers and other occupations), comorbidity status (at least one high-risk related disease or not), vaccination status (the no-vaccine scenario and the vaccination scenarios considering different vaccines and their respective schemes), and 12 infection-related states: susceptible (patients without immunity to SARS-CoV-2 or infection), exposed (patients exposed to SARS-CoV-2 in the incubation period), asymptomatic infected (infected with SARS-CoV-2 without symptoms; these subjects can propagate the infection), presymptomatic infected (infectious time before symptoms), symptomatic infected (infectious with symptoms), home-attended infected (infected with home care), hospitalized infected, infected in the intensive care unit, in recovery (a temporary compartment before recovery), recovered, immune, and dead. These were used to determine region-specific transmission rates according to the official population and transmission dynamics. Healthcare workers have a higher risk of infection than other professions in the simulation, given that they can be directly exposed to the virus when treating positive cases. We distributed the vaccine status considering time between doses, which may vary according to the vaccine and could also modify the total number of outcomes. We assume that the partially immune population has a reduced probability of death but still lacks the full protection of the vaccine. The code of the model is published in an open GitHub repository (https://github.com/alianzacaoba/CovidEconomicEvaluation).

The infection dynamics follow a susceptible-exposed-infectious-recovered–type discrete model. The susceptible population in each stratum enters the exposed compartment (for three days) and goes to the exposed compartments with a specific force of infection. This force of infection is greater in high-risk occupations (healthcare workers) and differs according to the region-specific calibration (see below). After the exposure period, the person changes to the presymptomatic or asymptomatic status according to an age-specific probability of developing symptoms. The asymptomatic period lasts ten days, after which the person is immune. The presymptomatic period lasts for 1.5 days, and then the person proceeds to the early symptomatic state for three days and then to an age- and comorbidity-specific probability of home, hospitalization, or critical care. Then, the patient dies with an age-, comorbidity-, and attention level–related probability or moves to a transition compartment before recovery. The subject is assumed to remain in recovery for 3 months, assuming the person is not a candidate to be vaccinated. After finishing the recovery period, the individual proceeds to the immune status. In our base-scenario, immune individuals do not return to the susceptible state or any other previous infection–related state. Appendix Figure 1 in Supplemental Materials found at https://dx.doi.org/10.1016/j.vhri.2022.04.004 presents the infection- and vaccination-related model dynamics. Infection and death risks vary across these strata; therefore, prioritization is needed to simultaneously reduce cases and deaths and consequently improve general health outcomes. We considered the five vaccines purchased by the government in the same published proportions, distributed as 22% Pfizer-BioNTech's BNT162b2 vaccine, 22% Oxford-AstraZeneca's Vaxzevria, 22% Moderna's mRNA-1273, 19% Janssen's JNJ-78436735, and 16% Sinovac's CoronaVac. We assume that 68.5 million doses are used to vaccinate 35 million residents in Colombia aged 16+ years given the safety and efficacy studies and information available.[4,5,7,8] This population corresponds to 100% of the current vaccination candidates. We assumed the same efficiency and effectiveness reported in the medical trials of each vaccine.[4,5,7,8]

The study is performed from the perspective of the third payer, the Colombia's healthcare system. As such, it only contemplates the direct costs associated with treatment of the patients and vaccine acquisition. The study measures the infection-related health effects in disability-adjusted life-years (DALYs).

We consider a comparative base-case of a no-vaccination scenario as a worst case, indicating that no immunization is available. As vaccination strategies, we choose two options. The first is a high-risk prioritization strategy in which the population receiving the vaccine have either high-risk of disease (healthcare workers) or high probability of death (elderly and people with comorbidities). The high-risk prioritization assumes that vaccination is done in three phases: (1) vaccination of healthcare personnel and people older than 70 years; (2) population younger than 70 years with comorbidities; and (3) population younger than 70 years without comorbidities. The second vaccine scenario (no prioritization) assumes a general vaccination rollout, without any specific priority, in which people of every age, work risk, and comorbidity risk are vaccinated simultaneously and in a proportional way.

Our simulations start with propagation from February 21, 2020 to April 15, 2021, when the vaccination starts. Then, the simulation runs until February 21, 2023 with vaccination. The data used to calculate our costs and DALYs for the cost-effectiveness analyses are captured from April 15, 2021 to the end of the simulation. Given the short time horizon, our model does not contemplate any discount rate for either costs or outcomes.

Table 1. Cases, burden of disease, and cost-effectiveness of high-risk prioritization of COVID-19 vaccination in Colombia.

Outcomes	No vaccination	High-risk prioritization	No prioritization
Cases and deaths, n (/100 000 pop.)			
Cases	204 988 (401.28)	114 532 (224.21)	162 779 (318.65)
Hospitalization	77 450 (151.61)	41 560 (81.36)	61 165 (119.74)
Critical care admissions	36 134 (70.73)	11 129 (21.79)	24 965 (48.87)
Deaths	36 163 (70.79)	14 444 (28.28)	24 082 (47.14)
Burden of disease			
Costs, US$ in millions	$163.54	$419.29	$470.55
DALYs	294 751	218 166	235 979
Avoided costs, US$ in millions	Ref.	$255.74	$307.00
Avoided DALYs	Ref.	76 585.64	58 771.86
Incremental cost-effectiveness ratio	Ref.	$3339.33	$5223.66

DALY indicates disability-adjusted life-year; pop., population; Ref., reference.

For the measurement of health benefits, we estimated DALYs. We used disability weights from the Global Burden of Disease study considering mild (0.006), medium (0.051), and severe pneumonia (0.133).[11] These DALYs are used to represent the loss of quality of life across the years, considering the time spent having the condition and years of life lost due to premature mortality. We considered our years of life lost in reference to Colombia's life expectancy (76 years). As a reference, one DALY represents the loss of 1 year of full health.

Our cost-effectiveness measure is the difference in costs divided by the averted DALYs compared with the comparative scenario (no vaccination). As a secondary analysis, we calculated the ratio between the two vaccination strategies. We consider a cost-effectiveness threshold of one GDP per averted DALY.

The data used to fit the model were gathered from different local, national, and international sources (see Appendix in Supplemental Materials found at https://dx.doi.org/10.1016/j.vhri.2022.04.004). The resident population in each department by age-group was obtained from data from the Ministry of Health,[12] whereas births and deaths were retrieved from the National Administrative Department of Statistics.[13] Deaths were considered by age-group and department. The yearly birth and all-cause death rates were transformed into daily rates following standard formulas.[14] The population with comorbidities was estimated through the percent of individuals with at least 1 relevant diagnosis according to claims data in a health insurance database.[15] The number of healthcare workers was calculated using data from the Ministry of Health.[16]

We estimated the probability of an individual developing symptoms based on the infection fatality rate[17] based on our calibrated simulation of symptomatic cases with data from the Colombian National Institute of Health up to October 25, 2020.[18] We used the contact matrix for Colombia estimated by Prem et al[19] and rescaled this contact matrix to the eight age groups used in the present study. The contact rates were further adjusted using Google Mobility Trends from the start of the model up to the simulated April 20, 2021.[20]

Costs were obtained from a health insurer in Colombia.[21] Two databases were used: the first details the COVID-19 patients as of November 21, 2020; the second takes the expenses for hospital care in 2020. In this study, we assume that COVID-19 costs are related to home, hospital, and intensive care unit treatment reported in US dollars (US$1 equals 3716.7 Colombian pesos, the exchange rate for May 29, 2021). Vaccination costs were assumed to have a base value of US$10 per vaccination scheme. This means that 2-dose vaccination schemes (BNT162b2, Vaxzevria, mRNA-1273, and Sinovac) are considered as US$5 per dose and JNJ-78436735 as US$10 for the single dose of the scheme. We defined cost-effectiveness based on the Colombian GDP in 2020 of US$5390.79.[22]

The model assumes that the vaccine-related immunity is not lost over time, and therefore, no reinforcements are needed in the simulation time window. Immune vaccinated individuals are not capable of becoming infected. The vaccinated individuals who do not develop complete immunity are susceptible to becoming infected but have a 0% probability of severe symptoms or death. Every region is assumed to be independent; hence, there is no migration of individuals (infected or not) between regions.

Model Calibration

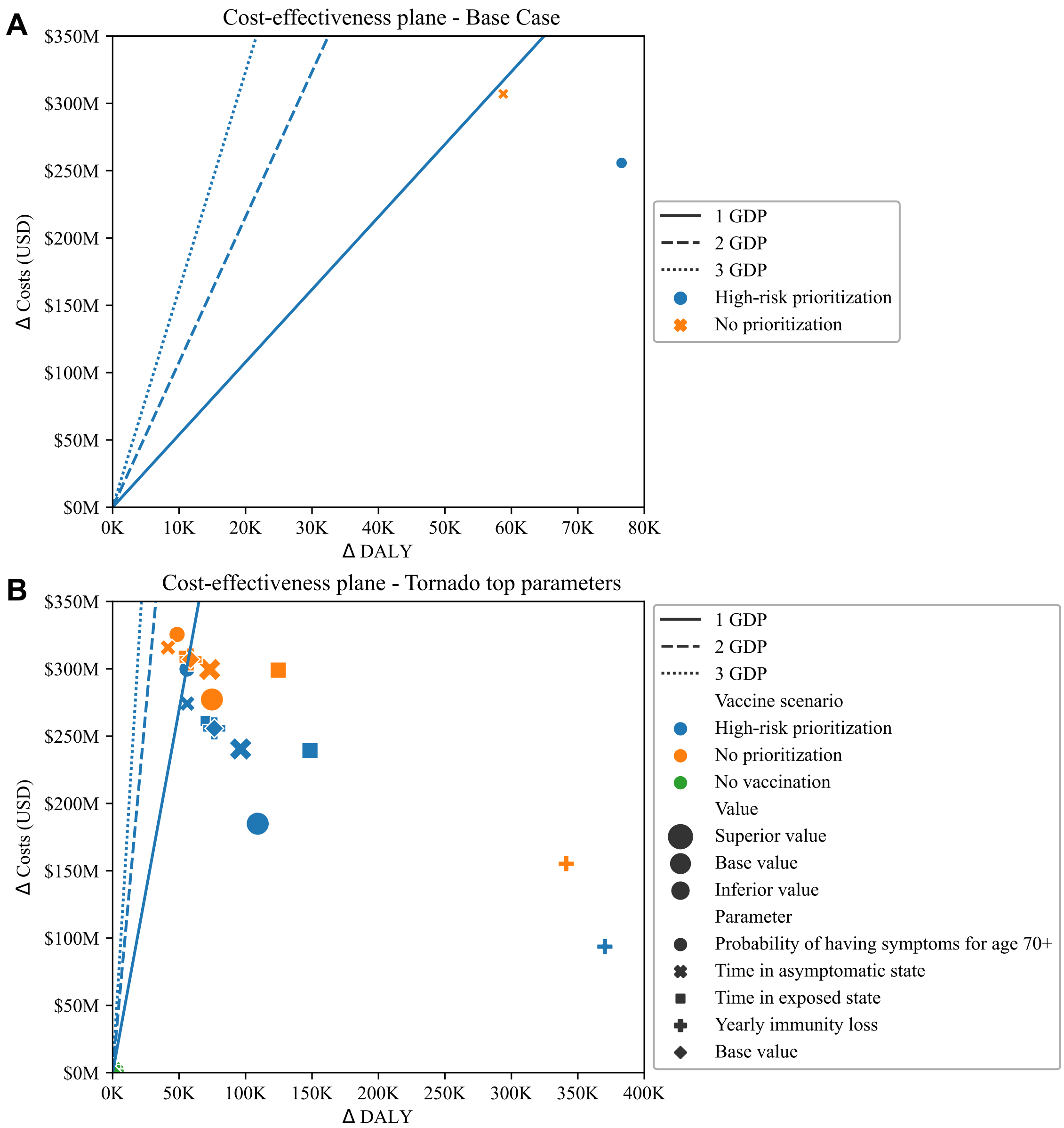
A calibration was made considering simulation-based optimization algorithms. The country was divided into six regions (North, Center, Bogotá DC, East, West, and South). These regions were selected based on the classification of the Colombian statistical agency, based on the geography and epidemiological burden of each region.[23] For each region, the calibration was made for three parameters in these six regions (the per-capita transmission rate, the national immigration rate, and underreporting of the case-fatality rate) and a national coefficient of change for the symptomatic probability, giving a total of 19 parameters to calibrate.

We selected seroprevalence, cumulative cases, and cumulative deaths in each region as calibration targets using data from the Colombian National Health Institute.[18] The loss function was the mean percent squared error. For the cases and deaths calibration targets, we only considered days with ≥ 50 cumulative cases. The optimal values were obtained by using a simulation-based optimization with a modified Nelder-Mead simplex algorithm.[24,25] This means we searched for the best fitting values that would decrease the difference between observed and modeled estimations. Appendix Figure 2 in Supplemental Materials found at https://dx.doi.org/10.1016/j.vhri.2022.04.004 presents the results of the fit.

Scenario Analysis

In addition to the three base scenarios, we included a set of various sensitivity analyses: (1) a univariate tornado analysis; (2) univariate analysis modifying the daily contacts, infection fatality rate (IFR), vaccine effectiveness, natural immunity loss, and

Figure 1. Cost-effectiveness plane for the base-case scenarios and top 4 relevant common parameters in the tornado analysis according to the ICER. Panel A shows how high-risk prioritization has both less costs and higher benefits. Panel B shows the scenarios of avoided cost and DALYs in different scenarios in the cost-effectiveness plane.



DALY indicates daily-adjusted life-year; GDP, gross domestic product; ICER, incremental cost-effectiveness ratio; K, thousand; M, million.

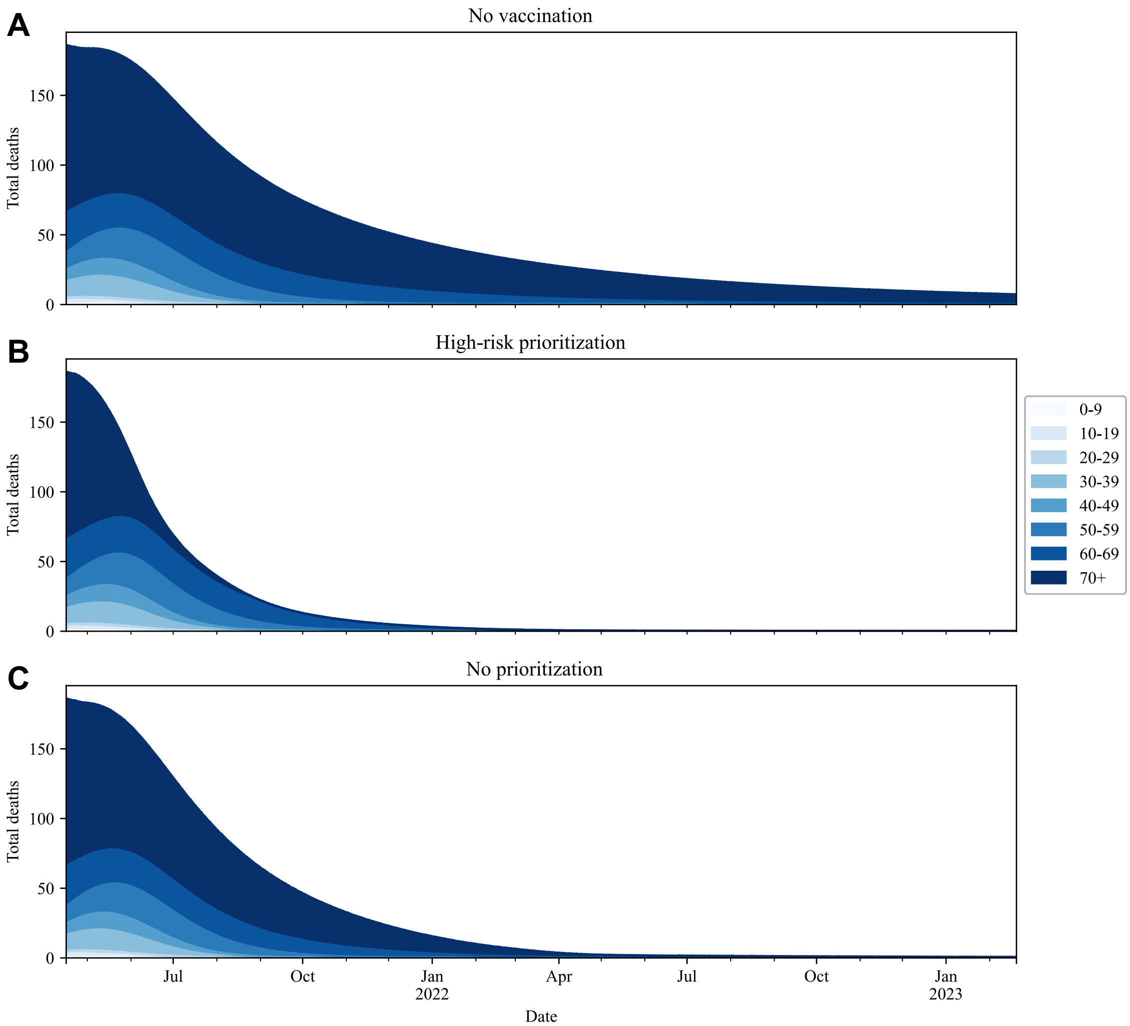
symptomatic probability; and (3) a bivariate analysis modifying vaccination end-date IFR, daily contacts-natural immunity loss, and daily contacts-vaccination end-date vaccine distribution. The natural immunity loss scenario assumes that vaccinated individuals may be reinfected; nevertheless, the death and critical care probability remains as 0. We assume that no booster vaccination doses are required.

Results

Base-Case Scenario

The vaccination strategy based on high-risk prioritization would avoid a total of 90 456 cases (114 532 cases compared with 204 988 in the no-vaccination scenario) and 21 719 deaths (14 444 deaths avoided compared with 36 163 deaths in the no-vaccination scenario). The no-prioritization strategy would avoid only 42 209 cases (with a total of 162 779 cases) and 12 082 deaths. These results are presented in Table 1. When we added costs in the equation, both vaccination strategies are cost-effective with a threshold of one GDP per averted DALY (Fig. 1A). The no-prioritization strategy shows a higher incremental cost-effectiveness ratio (ICER) (US$5223/averted DALY) than the high-risk prioritization strategy (US$3339/averted DALY) compared with the no-vaccination case; hence, the high-risk prioritization is presented as the most cost-effective of the strategies considered. Comparing both vaccination strategies, we find that the no-prioritization strategy is dominated by the high-risk

Figure 2. Percentage of deaths by age group, according to the vaccination scenario. Panel A shows what would occur in the no-vaccination scenario, Panel B in the high-risk scenario, and Panel C in the no-prioritization scenario. Panel B shows the shift in the age distribution of deaths to younger ages when prioritizing older ages. In Panel C, given that the allocation of vaccines is random, there is no large change in the distribution with higher vaccination coverage.



Apr indicates April; Jan, January; Jul, July; Oct, October.

prioritization strategy with an ICER of –US$2877.52/averted DALY. This means that the high-risk prioritization decreases the total amount of DALYs during the simulation period at a lower cost than implementing the no-prioritization option.

The no-vaccination scenario presents most deaths in the 70+-year-old age group (Fig. 2A), while the age-specific distribution of deaths high-risk prioritization scenario and without prioritization is shown in Figure 2 (Panel B and C, respectively). The highest number of deaths in the high-risk prioritization is estimated to occur in individuals younger than 15 years (Fig. 4B).

Uncertainty Analyses

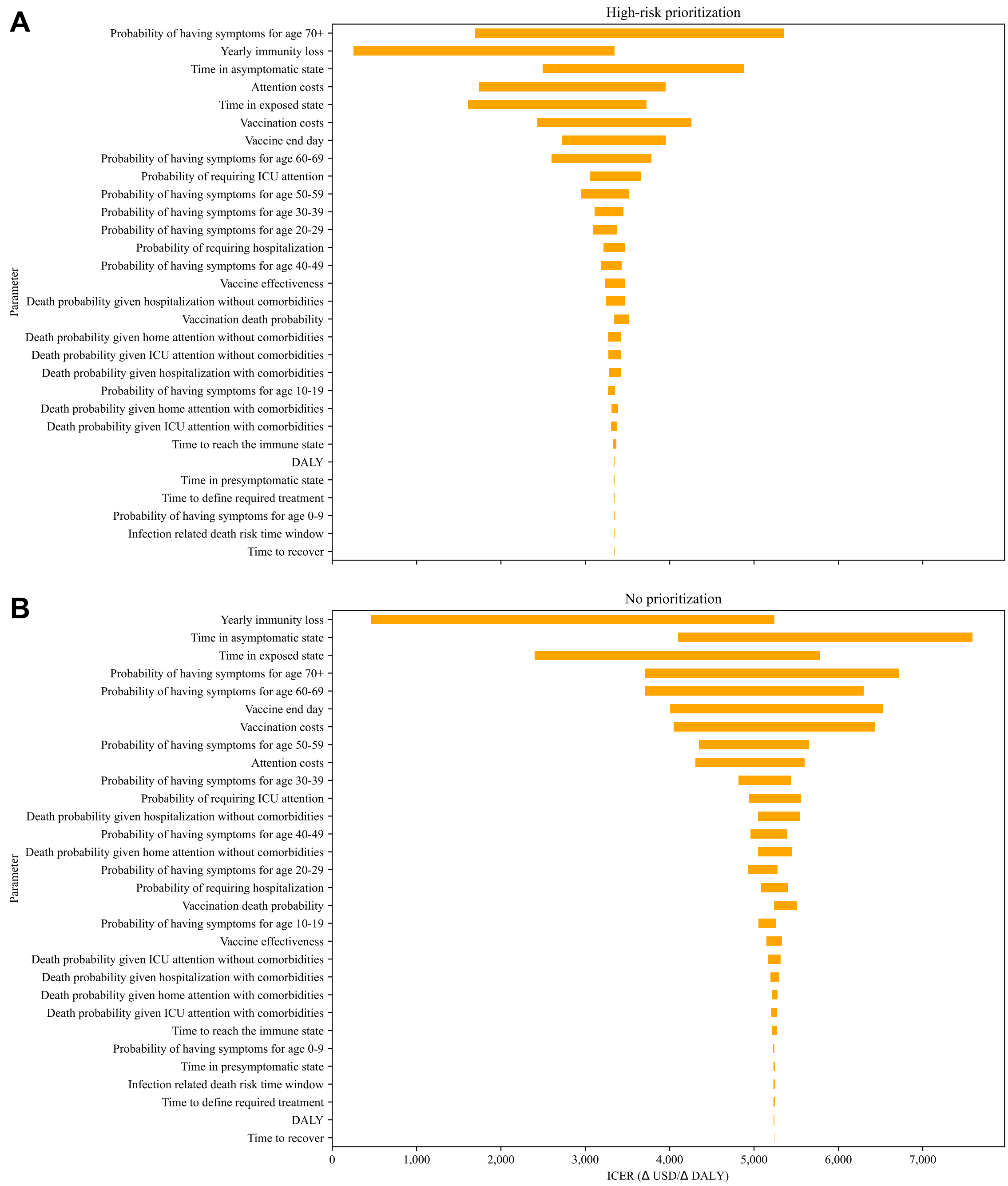
We tested the ICER variation for both strategies by varying 30 different parameters. The inferior and superior values considered all correspond to ±10% variation relative to the base-case values. Results of the ICER variation are presented in Figure 3A for the high-risk prioritization strategy and Figure 3B for the no-prioritization strategy. The four characteristics that most affect the model are (1) the probability of developing symptoms for the population aged 70+ years, (2) natural immunity loss, (3) time in the asymptomatic state, and (4) time in the exposed state. The cost-effectiveness plane of these simulations is presented in Figure 1B. The cost-effectiveness of the high-risk prioritization strategy is shown to be cost-effective (under the threshold of one GDP per averted DALY) for every case. This is the result of the reduction of cases in the no-vaccination scenario in such circumstances.

Univariate and Multivariate Sensitivity Analyses

When we assume immunity loss, there is an increase of the cost-effectiveness of both vaccination scenarios (Fig. 4A and Table 2). When there is 35% immunity loss per year, the high-risk prioritization strategy results in lower differential costs than having no vaccination. This same effect occurs in the no-prioritization scenario when the rate reaches a yearly loss of 40%.

A similar relation occurs when we change the probability of developing symptoms (Fig. 4B). The reduction of the symptomatic probability can change both strategies from

Figure 3. Tornado analysis of the ICER for each vaccination strategy. Panel A shows the probability of having symptoms among infected older than 70 years changes the model the most in the high-risk prioritization scenario. Panel B shows that the assumed immunity loss every year provides the most significant uncertainty in the scenario without prioritization of COVID-19 vaccination.



DALY indicates daily-adjusted life-year; ICER, incremental cost-effectiveness ratio; ICU, intensive care unit; IFR, infection fatality rate; USD, US dollar.

cost-effective to noncost-effective with a threshold of one GDP per averted DALY. This change is given by the fact that the reduction of the symptomatic probability simultaneously reduces averted severe cases and deaths. Consequently, vaccination would not result in a significant benefit for the national healthcare system. We also modified the IFR considering 10% and 20% increments and decrements over the base-case scenario (Fig. 4C). Assuming 10% and 20% increments and decrements in the IFR only affected the total DALYs but had a small (from 4.64% to 7.11%) effect on cost-effectiveness. Only the no-prioritization strategy became noncost-effective with a threshold of one GPD per averted DALY.

The results assuming the effect of change in contacts following the adherence to nonpharmacological interventions are presented in Figure 4D. The reduction of contacts appears to increase the cost-effectiveness of vaccination in both scenarios: the 50% contact reduction increases the avoided DALYs from 76 491.48 in the high-risk prioritization strategy and 58 599.66 in the

Table 2. Cases and deaths of the scenarios of no vaccination, high-risk prioritization, and loss of natural immunity in the model.

Yearly immunity loss, %	No vaccination		High-risk prioritization		No prioritization	
	Cases	Deaths	Cases*	Deaths*	Cases*	Deaths*
0 (base case)	2 701 514	108 194	2 611 060 (90 454; 3.35%)	86 476 (21 718; 20.07%)	2 659 307 (42 207; 3.35%)	96 113 (12 081; 20.07%)
5	2 997 655	117 732	2 901 602 (96 054; 3.2%)	88 862 (28 870; 24.52%)	2 947 959 (49 697; 3.2%)	99 434 (18 299; 24.52%)
10	3 289 968	127 036	3 188 525 (101 443; 3.08%)	91 210 (35 826; 28.2%)	3 233 060 (56 908; 3.08%)	102 682 (24 354; 28.2%)
15	3 578 524	136 111	3 471 896 (106 628; 2.98%)	93 519 (42 592; 31.29%)	3 514 673 (63 851; 2.98%)	105 860 (30 252; 31.29%)
20	3 863 394	144 966	3 751 777 (111 617; 2.89%)	95 790 (49 176; 33.92%)	3 792 858 (70 535; 2.89%)	108 969 (35 997; 33.92%)
25	4 144 645	153 606	4 028 228 (116 417; 2.81%)	98 024 (55 582; 36.19%)	4 067 675 (76 970; 2.81%)	112 011 (41 595; 36.19%)
30	4 422 343	162 037	4 301 309 (121 034; 2.74%)	100 220 (61 817; 38.15%)	4 339 180 (83 163; 2.74%)	114 987 (47 050; 38.15%)
35	4 696 555	170 266	4 571 080 (125 475; 2.67%)	102 381 (67 885; 39.87%)	4 607 431 (89 124; 2.67%)	117 900 (52 366; 39.87%)
40	4 967 342	178 298	4 837 596 (129 746; 2.61%)	104 507 (73 792; 41.39%)	4 872 482 (94 860; 2.61%)	120 751 (57 548; 41.39%)
45	5 234 767	186 139	5 100 915 (133 852; 2.56%)	106 597 (79 542; 42.73%)	5 134 387 (100 380; 2.56%)	123 540 (62 599; 42.73%)
50	5 498 889	193 795	5 361 089 (137 800; 2.51%)	108 653 (85 141; 43.93%)	5 393 199 (105 691; 2.51%)	126 271 (67 524; 43.93%)

Note. Cases are considered not just from the start of the vaccination period but in the whole simulation period, given the change throughout the complete simulation time window.
*n (absolute change; percent change relative to no vaccination).

no-prioritization strategy to 91 225.98 and 75 413.13, respectively. The ICER also presents an improvement from a cost of US$3343.44 to US$2820.33 per DALY in the most cost-effective solution. These estimations do not consider the overall economic effect on society of nonpharmacological interventions. Figure 4E shows that natural immunity loss has a higher effect on the cost-effectiveness than the nonmedical interventions.

The effects of varying vaccine effectiveness both by reducing the current effectiveness relative to current values and by assuming a fixed effectiveness for all available vaccines are presented in Figure 4F. The results presented show a small effect on the total DALYs but an observable change in total costs, which modifies the total cost-effectiveness of each policy. In the high-risk prioritization strategy, these costs range from the most efficient resource usage at US$245.81 million with 90% effectiveness of the vaccines to US$275.65 million when the effectiveness of the vaccines is considered to be 50% lower than the efficacy reported in the studies.

The effectiveness of these strategies does not only depend on the considered vaccines but also includes the rate at which the immunization plan is executed. The interaction between these rates, referenced to the month in which the vaccination should end (October 2021, January 2022, April 2022, and July 2022), with two relevant variables is presented in Figure 4G,H. When we accelerate the vaccination coverage to be completed in eight months (concluding by October 2021), our results show a 22.96% reduction in deaths and a 3.78% reduction in symptomatic cases in the high-risk prioritization scenario. The no-prioritization strategy increases the cost-effectiveness at a higher rate when there are both an increase in the speed of vaccination and a reduction in the contact rate. The effects on the cost-effectiveness appear to be higher under the no-prioritization strategy when these parameters vary than under the high-risk prioritization strategy. The cost-effectiveness improvement of both strategies suggests that both could be equally cost-effective under extremely rapid vaccination rates or a contact reduction of almost 100%; nevertheless, such policies are not considered because they do not represent realistic options in the context of Colombia.

Discussion

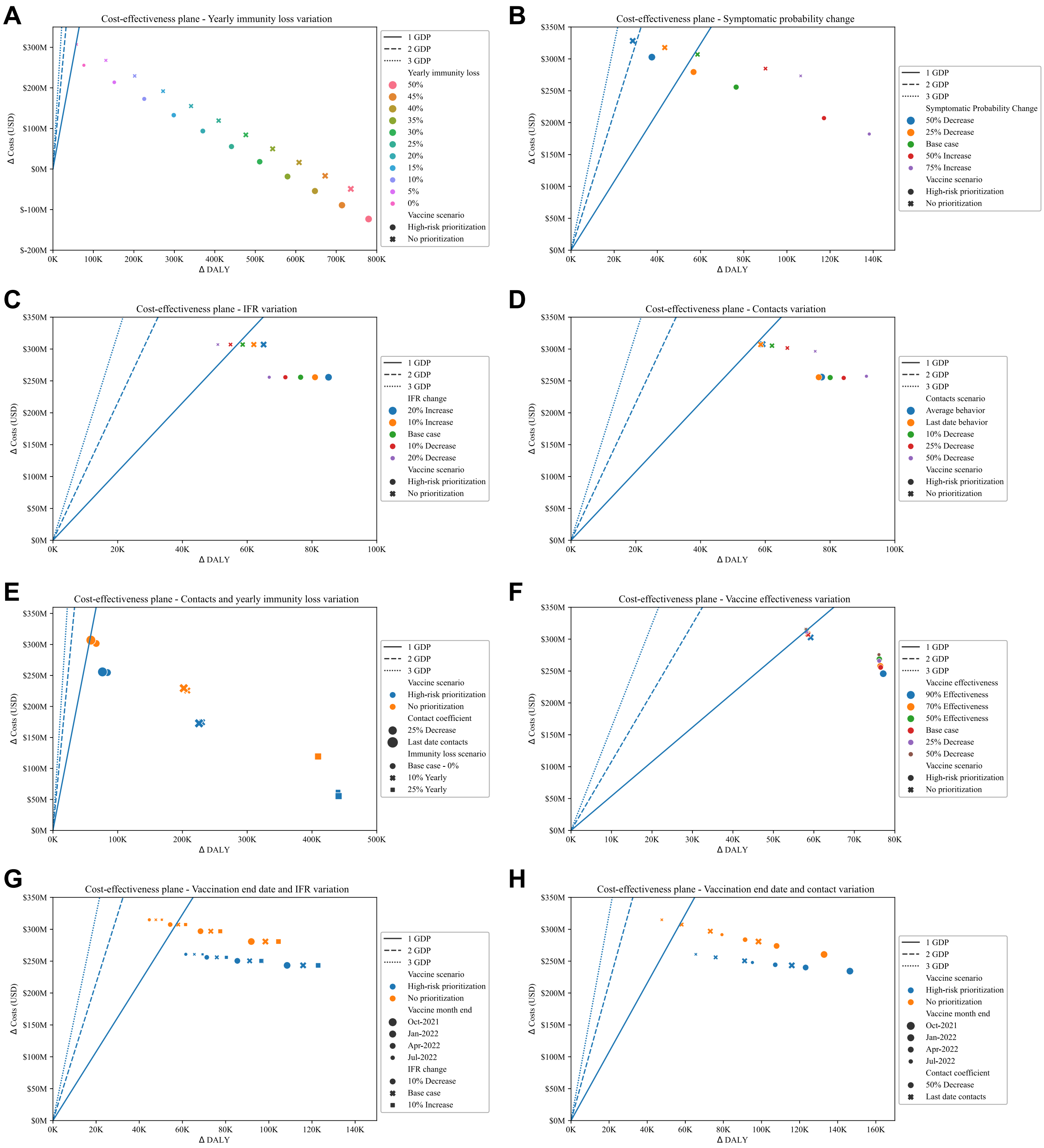
Both vaccination strategies proposed are cost-effective at the one GDP per averted DALY threshold. The high-risk prioritization presents both lower costs and a higher value of averted DALYs than the no-prioritization counterpart. The most cost-effective strategy presents an ICER of US$3339.33 per averted DALY. Throughout the different uncertainty and sensitivity scenarios, this ICER changed but the cost-effectiveness was never lost. In contrast, the no-prioritization strategy is highly sensitive to the parameter variations, changing the initial ICER of US$5223.66 to noncost-effective results with slight variations, considering a cost-effectiveness threshold of one GPD per averted DALY. This last strategy is dominated by the high-risk prioritization.

Vaccination with currently available SARS-CoV-2 vaccines provided protection against COVID-19 deaths in our model. We project that prioritization of vaccination among individuals at higher risk of COVID-19 mortality would provide the greatest reduction in deaths during the next 2 years after the start of vaccination. Nevertheless, the pace and speed of the projected and modeled rollout may not allow a large reduction of deaths during the timeframe. The projected high-risk prioritization strategy presented a 3.4% reduction of symptomatic cases and a 20.1% reduction of deaths over the course of the modeled period if vaccination ends after a year. These projections in the country do not consider the uncertainty about the transmission dynamics of variants of SARS-CoV-2 already circulating worldwide. Immunization is not considered for 32.5% of individuals because they are underage ($<$ 16 years old).

Nonpharmacological interventions such as quarantine or curfews may reduce cases and deaths but have economic consequences that exceed the scope of the study, and therefore, we did not evaluate the effects of other socioeconomic conditions such as unemployment, poverty, security, and hunger, among others. These economic effects are being seen alongside a reduction of GDP in countries worldwide.

The scenario without prioritization of COVID-19 vaccination provided almost no health benefits, according to our results. These

Figure 4. Cost-effectiveness plane for the uncertainty analyses.



Apr indicates April; DALY, daily-adjusted life-year; GDP, gross domestic product; Jan, January; Jul, July; K, thousand; M, million; Oct, October.

results are encouraging for decision makers in Colombia and middle-income countries worldwide, showing evidence that the prioritization of vaccine allocation and available resources increases the health benefits of COVID-19 vaccination.

There is large uncertainty about the effectiveness of some of the currently approved vaccines for the SARS-CoV-2 variants circulating worldwide (the variants alpha, beta, gamma, and delta). Although there is evidence suggesting that there is lower vaccine effectiveness for some of the variants,[26] the current evidence is not yet strong enough to be incorporated in the model as the main result. Nevertheless, in the timeframe of the study (up to February of 2023), assuming a yearly loss of natural immunity increases both cases and deaths in the three scenarios but also increases the avoided deaths, increasing the number of avoided DALYs.

The number of vaccines available is constrained by production capacity and cost. Therefore, countries are prioritizing medical workers and patients at higher risk of mortality and severe disease. Several studies have shown that older people, males, and individuals with diabetes, human immunodeficiency virus, cancer, chronic-obstructive pulmonary disease, and other diseases have increased risk of death if symptomatic with COVID-19. Our study considered prioritization of the population with these diseases, comparing them with the strategy of no prioritization and random allocation of vaccine doses. Our analyses provide evidence that this prioritization provides the greatest epidemiological and economic benefits.

Our study has limitations. First, our results are as reliable as our parameters. The uncertainty analysis of several parameters could change the cost-effectiveness of the decision; nevertheless, high-risk prioritization was found to be the dominant and robust solution throughout the study. Second, the perspective of our study is limited to the Colombian healthcare system. A societal perspective, by accounting for economic stability and other health-related conditions, would have allowed us to address the indirect impact of vaccination rates and the consequent reduction in cases and deaths on unemployment, poverty, and economic growth. Nevertheless, we limited our perspective to focus on the decisions of stakeholders in the healthcare system, knowing that, except for nonmedical interventions, every considered step would help in the restoration of previous conditions. One limitation is related to uncertainty about waning vaccine effectiveness over time: we did not assume vaccine immunity loss over time, which might lead to overestimation of the cost-effectiveness of the studied scenarios. Nevertheless, we consider our findings relevant in terms of cases, deaths, directly related health conditions, and efficient economic decisions for the government. A large strength of our findings is the consistency throughout the multiple sensitivity analyses performed. Indeed, we observed that the high-risk prioritization vaccination strategy was consistently cost-effective and dominant in our study under every analyzed parameter, except for the extreme values of change in the probability of symptomatic disease. Additionally, we observed that the no-prioritization strategy was not consistently cost-effective across the multiple sensitivity analyses, especially under the scenarios of changes in the probability of symptomatic disease and vaccination rate. These findings suggest that the high-risk prioritization vaccination strategy has a higher chance of being a cost-effective strategy in different scenarios, for example, across the heterogeneous health system infrastructure of Colombia.

Conclusion

The proposed optimization of high-risk population for COVID-19 vaccination in Colombia provides more health and economic benefits than the scenarios of no vaccination or no prioritization of vaccination. Increasing the speed of the vaccination rollout would increase the health and economic benefits of COVID-19 vaccination in this middle-income country.

Supplemental Materials

Supplementary data associated with this article can be found in the online version at https://dx.doi.org/10.1016/j.vhri.2022.04.004.

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REFERENCES

1. Dong E, Du H, Gardner L. An interactive web-based dashboard to track COVID-19 in real time. *Lancet Infect Dis*. 2020;20(5):533–534 [published correction appears in *Lancet Infect Dis*. 2020;20(9):e215].
2. Davies N, Kucharski A, Eggo R, Gimma A, Edmunds W. Centre for the Mathematical Modelling of Infectious Diseases COVID-19 working group. Effects of non-pharmaceutical interventions on COVID-19 cases, deaths, and demand for hospital services in the UK: a modelling study. *Lancet Public Health*. 2020;5(7):e375–e385.
3. Flaxman S, Mishra S, Gandy A, et al. Estimating the effects of non-pharmaceutical interventions on COVID-19 in Europe. *Nature*. 2020;584(7820):257–261.
4. Voysey M, Clemens S, Madhi S, et al. Safety and efficacy of the ChAdOx1 nCoV-19 vaccine (AZD1222) against SARS-CoV-2: an interim analysis of 4 randomised controlled trials in Brazil, South Africa, and the UK. *Lancet*. 2021;397(10269):99–111.
5. Baden L, El Sahly H, Essink B, et al. Efficacy and safety of the mRNA-1273 SARS-CoV-2 vaccine. *N Engl J Med*. 2021;384(5):403–416.

6. Dagan N, Barda N, Kepten E, et al. BNT162b2 mRNA Covid-19 vaccine in a nationwide mass vaccination setting. *N Engl J Med*. 2021;384(15):1412–1423.
7. Polack F, Thomas S, Kitchin N, et al. Safety and efficacy of the BNT162b2 mRNA Covid-19 vaccine. *N Engl J Med*. 2020;383(27):2603–2615.
8. Knoll M, Wonodi C. Oxford–AstraZeneca COVID-19 vaccine efficacy. *Lancet*. 2021;397(10269):72–74.
9. Li Q, Guan X, Wu P, et al. Early transmission dynamics in Wuhan, China, of novel coronavirus-infected pneumonia. *N Engl J Med*. 2020;382(13):1199–1207.
10. Global economic prospects. Resumen. https://www.bancomundial.org/es/publication/global-economic-prospects. Accessed December 23, 2020.
11. Institute for Health Metrics and Evaluation. *University of Washington. Healthdata – Global Burden of Disease*. University of Washington; 2021. https://vizhub.healthdata.org/gbd-results/.
12. Ministerio de Salud y Protección Social. Base de Datos Única de Afiliados (BDUA). 2012-2020;Vol 2020. https://servicios.adres.gov.co/BDUA/Consulta-Afiliados-BDUA.
13. Ministerio de Salud y Protección Social. Departamento Administrativo Nacional de Estadística. *Estadísticas Vitales*. 2012-2019;Vol 2020. https://www.dane.gov.co/index.php/servicios-al-ciudadano/281-demograficas/estadisticas-vitales.
14. Briggs A, Claxton K, Sculpher M. *Decision modelling for health economic evaluation*. Oxford, United Kingdom: Oxford University Press; 2006.
15. Ministerio de Salud y Protección Social. *Base de datos de la Suficiencia del Aseguramiento en Salud*. Vol. 2021; 2012-2018.
16. Ministerio de Salud y Protección Social. *Base de Datos del Registro Único Nacional de Talento Humano en Salud*. (ReTHUS). 2020. https://web.sispro.gov.co/THS/Cliente/ConsultasPublicas/ConsultaPublicaDeTHxIdentificacion.aspx.
17. Verity R, Okell L, Dorigatti I, et al. Estimates of the severity of coronavirus disease 2019: a model-based analysis. *Lancet Infect Dis*. 2020;20(6):669–677 [published correction appears in Lancet Infect Dis. 2020;20(6):e116].
18. Instituto Nacional de Salud. Base de datos de Casos. *COVID-19 en Colombia*; 2020. https://www.ins.gov.co/Noticias/Paginas/Coronavirus.aspx.
19. Prem K, Cook A, Jit M. Projecting social contact matrices in 152 countries using contact surveys and demographic data. *PLoS Comput Biol*. 2017;13(9):e1005697.
20. Google. *COVID-19 Community Mobility Reports*. https://www.google.com/covid19/mobility/.
21. *Mutual Ser EPS*. Mutual Ser EPS COVID-19 recorded cases. 2020.
22. Departamento Administrativo Nacional de Estadística. Producto Interno Bruto – Datos actualizados para. Vol. 2021. 2020; https://www.dane.gov.co/index.php/estadisticas-por-tema/cuentas-nacionales/cuentas-nacionales-trimestrales/pib-informacion-tecnica.
23. Departamento Administrativo Nacional de Estadística, ed. *Censo Nacional de Poblacion y Vivienda 2018*. Departamento Administrativo Nacional de Estadística; 2018. https://www.dane.gov.co/index.php/estadisticas-por-tema/demografia-y-poblacion/censo-nacional-de-poblacion-y-vivenda-2018.
24. Nelder J, Mead R. A simplex method for function minimization. *Comput J*. 1965;7(4):308–313.
25. Huang Y, McColl W. Improved simplex method for function minimization. *Proc IEEE Int Conf Syst Man Cybern*. 1996;3:1702–1705.
26. Davies N, Abbott S, Barnard R, et al. Estimated transmissibility and impact of SARS-CoV-2 lineage B.1.1.7 in England. *Science*. 2021;372(6538).eabg3055.