

Maintaining face mask use before and after achieving different COVID-19 vaccination coverage levels: a modelling study

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Summary

Background Face mask wearing has been an important part of the response to the COVID-19 pandemic. As vaccination coverage progresses in countries, relaxation of such practices is increasing. Subsequent COVID-19 surges have raised the questions of whether face masks should be encouraged or required and for how long. Here, we aim to assess the value of maintaining face masks use indoors according to different COVID-19 vaccination coverage levels in the USA.

Methods In this computational simulation-model study, we developed and used a Monte Carlo simulation model representing the US population and SARS-CoV-2 spread. Simulation experiments compared what would happen if face masks were used versus not used until given final vaccination coverages were achieved. Different scenarios varied the target vaccination coverage (70–90%), the date these coverages were achieved (Jan 1, 2022, to July 1, 2022), and the date the population discontinued wearing face masks.

Findings Simulation experiments revealed that maintaining face mask use (at the coverage seen in the USA from March, 2020, to July, 2020) until target vaccination coverages were achieved was cost-effective and in many cases cost saving from both the societal and third-party payer perspectives across nearly all scenarios explored. Face mask use was estimated to be cost-effective and usually cost saving when the cost of face masks per person per day was ≤US\$1.25. In all scenarios, it was estimated to be cost-effective to maintain face mask use for about 2–10 weeks beyond the date that target vaccination coverage (70–90%) was achieved, with this added duration being longer when the target coverage was achieved during winter versus summer. Factors that might increase the transmissibility of the virus (eg, emergence of the delta [B.1.617.2] and omicron [B.1.1.529] variants), or decrease vaccine effectiveness (eg, waning immunity or escape variants), or increase social interactions among certain segments of the population, only increased the cost savings or cost-effectiveness provided by maintaining face mask use.

Interpretation Our study provides strong support for maintaining face mask use until and a short time after achieving various final vaccination coverage levels, given that maintaining face mask use can be not just cost-effective, but even cost saving. The emergence of the omicron variant and the prospect of future variants that might be more transmissible and reduce vaccine effectiveness only increases the value of face masks.

Funding The Agency for Healthcare Research and Quality, the National Institute of General Medical Sciences, the National Science Foundation, the National Center for Advancing Translational Sciences, and the City University of New York.

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Introduction

Although many people in the USA adopted face mask wearing during the COVID-19 pandemic beginning in April, 2020, the spring of 2021 saw the relaxation of such practices, despite vaccination rates being well below potential herd-immunity thresholds.^{1–4} For example, in mid-May, 2021, the Centers for Disease Control and Prevention indicated that people who were vaccinated no longer needed to wear face masks while indoors in public, which prompted many individuals who were vaccinated or unvaccinated to stop wearing face masks.^{5,6} Subsequent COVID-19 surges, such as the ones fuelled by the delta (B.1.617.2) and omicron (B.1.1.529) variants,

did prompt the reinstitution of face mask requirements to some degree in certain jurisdictions, such as Los Angeles County, CA, and Washington, DC.^{7–9} However, face mask use in 2021 remained lower than it was in 2020, even though evidence has shown how face masks can potentially decrease the amount of SARS-CoV-2 particles that an infectious person can emit into the surroundings.¹⁰ Face masks might also reduce the amount of virus that the wearer of a face mask inhales.¹⁰ This decrease in viral particles, in turn, could decrease the transmission of SARS-CoV-2 and the resulting burden of COVID-19.^{10,11} Therefore, the question is whether face mask use should be encouraged or even

Lancet Public Health 2022;
7: e356–65

Published Online
March 8, 2022
[https://doi.org/10.1016/S2468-2667\(22\)00040-8](https://doi.org/10.1016/S2468-2667(22)00040-8)

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Research in context

Evidence before this study

We searched MEDLINE via PubMed on Sept 28, 2021, with key terms such as “face masks”, “COVID-19”, “SARS-CoV-2”, and “non-pharmaceutical interventions”, for studies (restricted to the English language) published between Dec 1, 2019, and Sept 28, 2021, assessing the impact and value of wearing face masks on SARS-CoV-2 transmission and subsequent clinical and economic outcomes. Previous studies have shown that face masks can decrease transmission of SARS-CoV-2, including laboratory studies and retrospective observational studies. However, it has not been clear what the value of maintaining more widespread face mask use might be across a wide range of different circumstances, especially when vaccination coverage has reached different levels. There has also been a scarcity of economic studies on face mask use that in turn could help better guide policy making, such as decisions on whether to institute mask requirements.

Added value of this study

Our study estimated that maintaining face mask use (at the levels seen in the USA from March, 2020, to July, 2020) until target vaccination coverages were achieved was cost-effective and in many cases cost saving from both the societal and third-party payer perspectives across nearly all scenarios explored. For example, it was always cost-effective and usually cost saving when the cost of face masks per person per day was \$1.25 or less. In fact, in all scenarios, it was cost-effective to maintain face

mask use for somewhere from 2 weeks to 10 weeks beyond the date that target vaccination coverage was achieved, with this added duration being longer when the target coverage was achieved during winter versus summer. Our results also showed that anything that could increase the transmissibility of the virus (eg, emergence of the delta [B.1.617.2] and omicron [B.1.1.529] variants), or decrease vaccine effectiveness (eg, waning immunity and escape variants), or increase social interactions among certain segments of the population, only increased the cost savings or cost-effectiveness provided by maintaining face mask use. Even if 100% of people who are symptomatic and infectious isolated, maintaining face masks remained cost saving or cost-effective.

Implications of all the available evidence

Available evidence supports maintaining face mask use to at least the levels seen in the USA from March, 2020, to July, 2020, until and beyond various target vaccination coverages. Recent developments in the pandemic, such as the emergence of the delta and omicron variants and the finding that vaccine protection wanes over time only further increases the value of face masks. Therefore, there could be substantial value in providing incentives for or requiring the use of face masks indoors. Since such use would be cost-effective and even cost saving across many different circumstances, governments, businesses, and third-party payers might consider subsidising the purchases of such face masks.

required in public indoor locations such as grocery stores and public transportation, and how long this encouragement or these requirements should be maintained. To address this question and simulate different scenarios of face mask wearing, we developed and used a computational Monte Carlo simulation model representing the USA and the impact of SARS-CoV-2.

Methods

Model structure

For this computational simulation-model study, we adapted our previously described stochastic computational model^{12–15} (developed in Microsoft Excel with the Crystal Ball add-in) that represented the spread and impact of SARS-CoV-2 in the USA with a population of 327 167 434 people. The initial model structure and how people mix with each other is presented (appendix p 1). The figure also shows the different mutually exclusive compartments that each person can be in on a given simulated day and the equations that govern how and when an individual will move among them. For example, an individual can move from being susceptible to exposed when they interact with an individual who is infectious on the basis of the following equation:

$$(\beta \times S \times I_s) + (\beta \times S \times I_a)$$

where β is the transmission coefficient and equals R_t divided by the infectious period duration in turn divided by population size. R_t is the reproduction number of the virus on a given day t and is the basic reproduction number (R_0 ; average number of secondary cases generated by one infectious case in a completely susceptible population), adjusted by observed seasonal variation. S is the number of individuals who are susceptible, and I is the number of individuals who are infectious. When an individual eventually becomes infectious, they have a probability of being asymptomatic (I_s) or symptomatic (I_a).

Each person who is symptomatic in turn travels through a probability tree of different possible sequential age-specific COVID-19 clinical outcomes (appendix p 1).^{12–17} The probabilities along with their distributions for each of the branches in the tree are provided here (appendix pp 4–6). Although the initial model structure attempted to account for the less heterogenous mixing that has been occurring during the pandemic because of COVID-19 precautions, additional iterations of the model explored the effects of further stratifying the population by age (an example of a model stratified by children and adults is shown on appendix p 2) and giving different age groups different mixing patterns with each other following previous studies.^{18,19}

See Online for appendix

Vaccination

As described in previous publications,^{12–15} getting vaccinated decreases the risk of an individual getting infected when interacting with someone who is infectious by 1 minus the vaccine efficacy at preventing infection. Once infected, an individual who is vaccinated has a lower probability (1 – vaccine efficacy at preventing severe disease; appendix p 5) of more severe outcomes. Such protection begins 2 weeks after vaccination.^{20–22} Vaccination has various probabilities of causing minor (eg, fever, soreness, or headache) and major (eg, allergic reaction or anaphylaxis, pericarditis, or myocarditis resulting in hospital admission and treatment) side-effects.

Face masks

Each day, any individual, whether vaccinated or unvaccinated, can wear face masks, which in turn decreases the probability of transmission between an individual who is infectious and one who is susceptible to infection proportionally by face mask effectiveness (appendix p 5).²³ Wearing face masks in turn attenuates R_t (ie, the average number of cases generated by one infectious case at a time t) by 1 minus effectiveness of face masks, with effectiveness being face mask efficacy multiplied by compliance with their use. For our baseline scenario, we assumed an estimated effectiveness of 18% (95% CI 16–20%)²³ reported from March to July, 2020. This estimated effectiveness translates to a compliance of 28·4% (95% CI 25·3–31·6%), when considering the type of masks used (ie, N95, surgical, or cloth), their reported use (appendix p 5),²⁴ and their reported efficacy (99% for N95 masks, 59% for surgical masks, and 51% for cloth masks)²⁵ during the same time period.

Costs

Each time any event or outcome (eg, vaccination, hospital admission and treatment, and death) occurred in a model run, it accrued corresponding costs and health effects. These costs and health effects are presented here (appendix pp 4–6). The perspective of the third-party payer includes direct medical costs (eg, hospital admission and treatment), whereas the societal perspective includes direct and indirect costs (ie, productivity losses caused by absenteeism and presenteeism). For each scenario, we calculated the incremental cost-effectiveness ratio (ICER) of scenario A versus scenario B as:

$$\text{ICER} = \frac{(\text{Cost}_{\text{face mask use A}} - \text{Cost}_{\text{face mask use B}})}{(\text{Health effects}_{\text{face mask use B}} - \text{Health effects}_{\text{face mask use A}})}$$

where health effects are measured in quality-adjusted life years (QALYs) lost. Death results in the loss of the net present value of QALYs for the remainder of an individual's lifetime.²⁶ We considered face mask use to be cost-effective if the ICER was up to US\$50 000 per

QALY. All costs are reported in 2021 values, inflating all past costs and discounting all future costs using a 3% annual rate.

Experimental scenarios

Each scenario simulated the entire course of the pandemic to date in the USA (model validation on appendix p 2), using reported case data and adjusting for potential underreporting on the basis of data used in our work with the New York Times.^{27–29} Each simulation experiment consisted of running the model 1000 times (Monte Carlo simulations) with each parameter drawing values from the distributions (appendix pp 4–6), and comparing what would happen if face masks were used as they were in March, 2020, to July, 2020, in the USA with what would happen with no mask use until various final vaccination coverages were achieved. Different scenarios varied the target vaccination coverage of the entire population (70–90%), the date this coverage was achieved (defined as 2 weeks after vaccination coverage occurred to account for the lag time required to achieve immune protection, varied from Jan 1, 2022, to July 1, 2022), and the date the population discontinued wearing face masks. In sensitivity analyses, we varied R_0 (2·5–10·0)^{30–36} to account for different possible variants, vaccine efficacy to prevent infection (30–90%) to account for waning immunity and different variants, natural immunity after infection (64–95%),^{37–42} and different face mask characteristics, such as face mask effectiveness, cost, and replacement frequency (baseline \$0·32 per person per day). Additional scenarios explored the percentage of people who self-isolated when infected.

Role of the funding source

The funders of the study did not have any role in the study design, data collection, data analysis, data interpretation, or writing of the report.

Results

Maintaining face mask use (at the amount of use seen in the USA from March, 2020, to July, 2020) until target vaccination coverages were achieved was cost-effective and in many cases cost saving across nearly all scenarios explored. For example, it was always cost-effective and usually cost saving when the cost of face masks per person per day was up to \$1·25. In fact, in all scenarios, it was cost-effective to maintain face mask use for about 2–10 weeks beyond the date that target vaccination coverage was achieved, with this added duration being longer when target coverage was achieved during winter versus summer. What follows are the major drivers that affected the findings.

The value of face masks increased in more than a linear manner as final vaccination coverage decreased (figures 1, 2). If the USA were to achieve an 80% vaccine coverage by March 1, 2022, simulations show that maintaining face mask use until then would avert

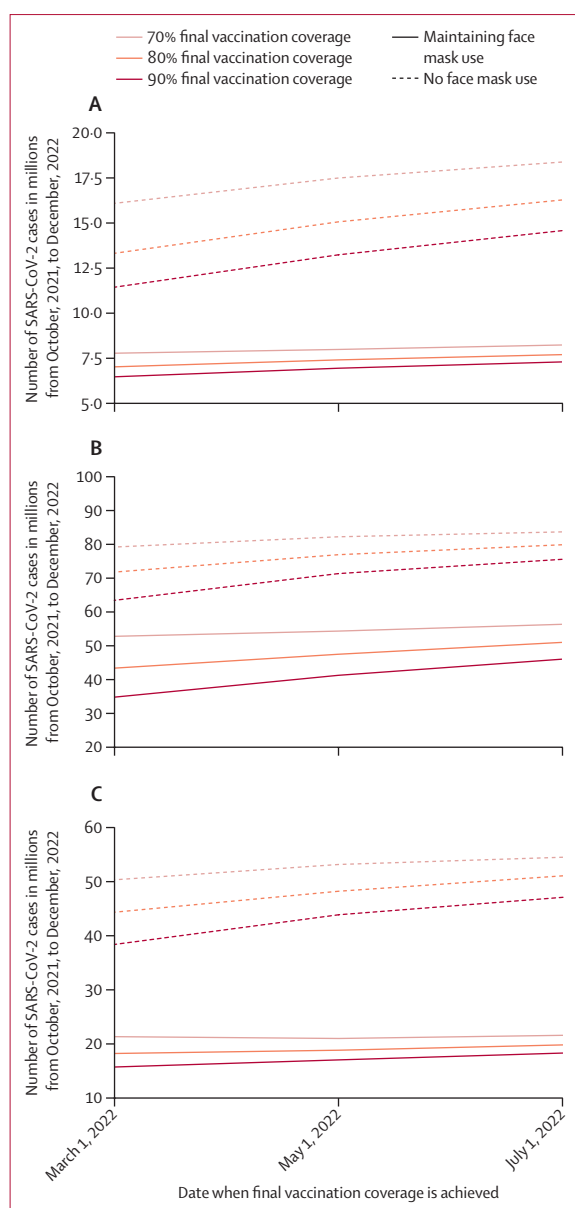


Figure 1: Simulated number of SARS-CoV-2 cases with and without face masks at different vaccination coverages

(A) Vaccination with 70% efficacy against infections, with SARS-CoV-2 $R_0=5$.
 (B) Vaccination with 70% efficacy against infections, with SARS-CoV-2 $R_0=8$.
 (C) Vaccination with 50% efficacy against infections, with SARS-CoV-2 $R_0=5$.
 Vaccination coverage is defined as the time at which immune protection was achieved, 2 weeks after vaccination.

US\$14.6 billion (95% CI 13.8–15.3) in societal costs and \$2.3 billion (95% CI 2.2–2.4) in third-party payer costs as well as 6.29 million (95% CI 6.28–6.3) cases, 138 600 (95% CI 137 600–139 700) hospital admissions and treatment, and 16 100 (95% CI 15 900–16 300) deaths, saving 180 000 (95% CI 172 500–187 600) QALYs (70% vaccine efficacy to prevent infection; these outcomes per 100 000 people are shown in the table; figures 1, 2). However, achieving only a 70% coverage would increase

these savings to \$20.6 billion (19.8–21.5) in societal costs, \$3.27 billion (3.20–3.34) in third-party payer costs, 8.3 million (8.29–8.34) cases, 193 500 (192 100–194 800) hospital admissions and treatment, 22 700 (22 500–22 900) deaths, and 252 900 (243 700–262 000) QALYs.

If the USA were to achieve a 90% coverage by May 1, 2022, simulations show that face mask use would avert \$13.3 billion (12.5–14.1) in societal costs and \$2.4 billion (2.2–2.5) in third-party payer costs, as well as 6.29 million (6.27–6.30) cases, 136 700 (135 700–137 800) hospital admissions and treatment, and 16 000 (15 700–16 100) deaths, saving 181 500 (173 900–198 200) QALYs (figures 1, 2). These savings would increase to \$16.7 billion (15.9–17.5) in societal costs, \$2.9 billion (2.8–3.1) in third-party payer costs, 7.66 million (7.63–7.69) cases, 174 900 (173 700–176 100) hospital admissions and treatment, 20 500 (20 300–20 700) deaths, and 223 700 (215 100–232 400) QALYs if only achieving 80% coverage (figures 1, 2).

For a given final vaccination coverage level, the longer it takes to reach that level, the greater the value of face masks (figures 1, 2; table). For example, as shown, if an 80% vaccination coverage is achieved at May 1, 2022 (70% vaccine efficacy), maintaining face masks until then would avert 7.66 million cases. However, if this same coverage was reached 2 months later on July 1, then these results change to \$18.7 billion (17.8–19.5) in societal costs, \$3.3 billion (3.2–3.5) in third-party payer costs, 8.57 million (8.55–8.60) SARS-CoV-2 cases, 200 000 (198 000–201 000) hospital admissions and treatment, and 23 200 (23 000–23 500) deaths averted, saving 264 000 (255 000–274 000) QALYs (figures 1, 2).

Varying R_0 showed that the emergence of more transmissible variants such as the delta and now omicron variants has further boosted the value of face masks (figure 1). For example, as aforementioned, when the R_0 is 5, corresponding to the delta variant, maintaining face masks would avert \$20.6 billion (19.8 to 21.5) in societal costs (70% coverage by March 1, 2022). A higher R_0 of 10, corresponding to the omicron variant, pushes these numbers averted up to \$49.5 billion (43.6 to 55.4) in societal costs, \$5.2 billion (5.0 to 5.4) in third-party payer costs, and 17.9 million (17.8 to 18.1) cases versus no mask use and maintaining 1 more month (until April) provided value, averting an additional \$1.5 billion (–13.7 to 6.8) in societal costs, \$148.6 million (–10.4 to 307.6) in third-party payer costs, and 856 000 (710 200 to 1 000 000) cases. Lowering the R_0 to 2.5, corresponding to the original virus, would lower these values to 581 350 (578 950 to 583 800) cases and face mask use would not be cost-effective.

The emergence of variants and waning immunity might also reduce vaccine effectiveness, which in turn will also increase the value of face masks (figures 1, 2; table). For example, with a 50% vaccine efficacy, maintaining face mask use until reaching a 70% coverage by March 1, 2022 would avert \$82.3 billion (79.7–84.9) in societal costs and \$9.1 billion (8.9–9.2) in third-party

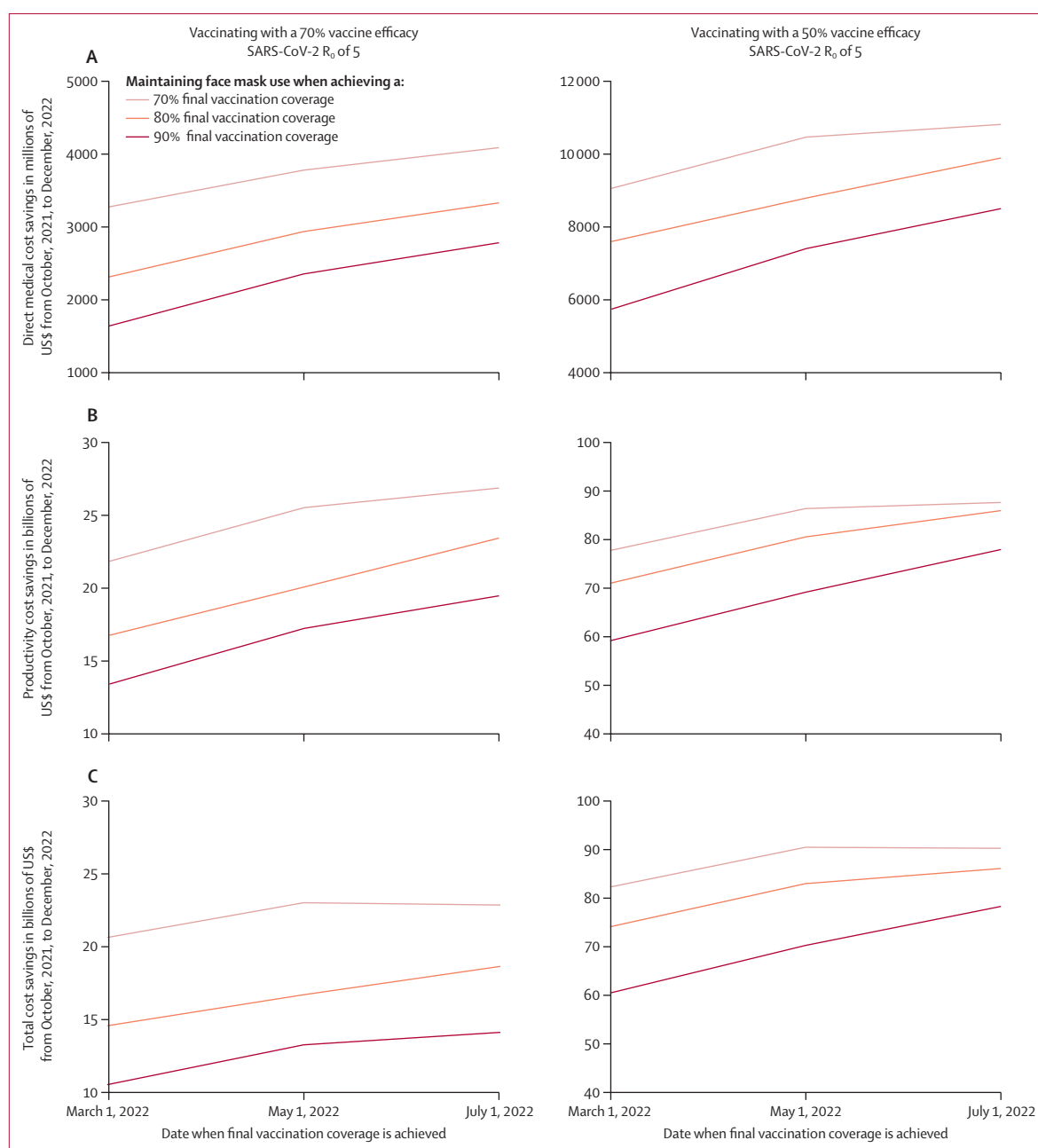


Figure 2: Estimated cost savings associated with maintaining face mask use

(A) Direct medical cost savings when maintaining face mask use. (B) Productivity cost savings when maintaining face mask use. (C) Total societal cost savings when maintaining face mask use. Final coverage defined as when immune protection is achieved, 2 weeks after vaccination.

payer costs as well as 29.1 million (28.8–29.5) SARS-CoV-2 cases, 533 500 (527 700–539 300) hospital admissions and treatment, and 62 600 (61 800–63 300) deaths, saving 737 900 (714 700–762 200) QALYs. As another example, with a 30% efficacy, face mask use until reaching a 70% coverage by March 1, 2022 would avert \$95.1 billion (90.2–100.0) in societal costs, \$10.7 billion (10.5–10.9) in third-party payer costs, and 34.0 million (33.7–34.3) cases. Maintaining masks for 2 more

months until May would be cost-effective (ICER \$48 421 per QALY) averting an additional 1.2 million (0.9–1.6) cases compared to maintaining masks for 1 additional month (figure 3). Even with a 90% vaccine efficacy, face mask use provided value, averting \$1.7 billion (1.4–2.1) in societal costs, \$1.0 billion (0.9–1.1) in third-party payer costs, and 1.93 million (1.92–1.93) cases compared to no mask use when achieving coverage by March 1, 2022 (figures 1–3).

	Total SARS-CoV-2 infections (per 100 000 people)	Hospital admissions and treatment (per 100 000 people)	Deaths (per 100 000 people)	QALYs lost (per 100 000 people)	Direct medical costs (in millions of US\$ per 100 000 people)	Productivity losses (in millions of US\$ per 100 000 people)
70% vaccination coverage achieved by Jan 1, 2022, with 70% vaccine efficacy to prevent infection						
No face mask use	4365.4 (4317.5–4391.4)	103.8 (100.7–106.8)	12.2 (11.5–12.7)	134.1 (105.6–166.0)	3.8 (3.6–4.0)	12.4 (10.0–14.5)
Using face masks until reaching the target vaccination coverage	2473.4 (2342.3–2575.1)	60.4 (57.7–63.0)	7.1 (6.7–7.5)	76.1 (59.0–93.3)	3.1 (2.9–3.3)	7.2 (6.0–8.6)
Using face masks for 1 month after reaching target vaccination coverage	2300.4 (2209.3–2371.2)	56.8 (54.3–59.0)	6.6 (6.2–7.0)	72.2 (56.0–89.1)	3.1 (2.9–3.3)	6.9 (5.6–8.0)
70% vaccination coverage achieved by March 1, 2022, with 50% vaccine efficacy to prevent infection						
No face mask use	15 526.6 (14 409.9–16 540.3)	294.0 (273.0–317.1)	34.3 (31.8–37.0)	388.7 (311.1–476.5)	7.1 (6.7–7.5)	40.6 (33.9–49.6)
Using face masks until reaching the target vaccination coverage	6486.4 (6275.3–6729.1)	130.7 (125.1–136.6)	15.2 (14.4–16.1)	167.2 (131.4–210.4)	4.3 (4.1–4.5)	18.0 (14.9–21.4)
Using face masks for 1 month after reaching target vaccination coverage	6162.2 (5962.5–6385.0)	124.3 (118.8–130.2)	14.6 (13.7–15.4)	160.3 (128.1–200.4)	4.2 (4.0–4.4)	16.8 (14.0–20.2)
80% vaccination coverage achieved by March 1, 2022, with 90% vaccine efficacy to prevent infection						
No face mask use	1689.8 (1674.5–1721.9)	51.9 (50.4–53.5)	6.0 (5.8–6.4)	64.1 (49.4–81.0)	4.5 (4.1–4.9)	5.9 (5.0–6.9)
Using face masks until reaching the target vaccination coverage	1210.1 (1191.0–1239.0)	37.1 (36.0–38.4)	4.3 (4.1–4.5)	46.1 (35.8–58.5)	4.3 (3.9–4.6)	4.6 (3.9–5.4)
Using face masks for 1 month after reaching target vaccination coverage	1208.0 (1189.1–1234.0)	37.1 (35.8–38.4)	4.3 (4.1–4.5)	45.8 (36.4–58.0)	4.2 (3.9–4.6)	4.6 (3.9–5.5)
80% vaccination coverage achieved by March 1, 2022, with 70% vaccine efficacy to prevent infection						
No face mask use	4091.2 (4038.8–4119.0)	95.4 (92.3–98.5)	11.1 (10.6–11.7)	121.3 (95.5–151.1)	5.2 (4.9–5.6)	12.1 (9.9–14.4)
Using face masks until reaching the target vaccination coverage	2150.3 (2104.1–2195.5)	52.9 (51.1–54.8)	6.2 (5.9–6.5)	68.0 (52.2–84.4)	4.5 (4.1–4.9)	7.0 (5.9–8.4)
Using face masks for 1 month after reaching target vaccination coverage	2138.3 (2089.1–2184.8)	52.9 (51.0–54.5)	6.1 (5.9–6.5)	67.3 (54.1–84.7)	4.5 (4.1–4.9)	7.0 (5.9–8.3)
80% vaccination coverage achieved by July 1, 2022, with 50% vaccine efficacy to prevent infection						
No face mask use	15 646.6 (14 536.2–16 743.6)	299.6 (275.5–319.3)	34.7 (31.9–37.5)	388.6 (306.6–481.5)	8.7 (8.2–9.2)	41.9 (34.3–50.5)
Using face masks until reaching the target vaccination coverage	6004.9 (5786.5–6258.1)	122.5 (116.8–128.8)	14.3 (13.5–15.2)	156.4 (125.6–197.0)	5.7 (5.3–6.0)	17.1 (14.1–20.4)
Using face masks for 1 month after reaching target vaccination coverage	5984.0 (5780.2–6234.5)	122.4 (116.9–128.4)	14.3 (13.4–15.1)	160.7 (128.5–198.4)	5.7 (5.3–6.1)	16.9 (13.9–20.3)

Data are presented as median (IQR). The date at which vaccination coverage is achieved occurs 2 weeks after vaccination to account for the 2 weeks that it might take for the full onset of immune protection. Results are the number of cases, clinical, and economic outcomes occurring from October, 2021, to December, 2022.

Table: Difference between not wearing face masks and maintaining face mask use when achieving target vaccination coverages at different dates with different vaccine efficacies

Increasing the effectiveness of face masks (eg, average compliance of 44.2%), decreased the total number of infections when using masks and thus increased the value of face mask wearing. For example, when an 80% vaccination coverage was achieved by March 1, 2022 (vaccine efficacy 70%; $R_0=5$) maintaining face mask use averted \$18.0 billion (17.3–18.7) in societal costs and \$3.0 billion (2.9–3.1) in third-party payer costs, as well as 8.15 million (8.14–8.17) cases, 179 400 (178 400–180 400) hospital admissions and treatment, and 20 900 (20 700–21 100) deaths, saving 235 900 (228 800–242 900) QALYs.

Mask use in March, 2020, to July, 2020, with that particular combination of N95, surgical, and cloth masks, would have resulted in a cost per person per day of \$0.32. Adjusting different usage and characteristics (eg,

frequency of replacement and cost per mask; appendix p 8) so that the cost per person per day increased to \$0.94 resulted in decreases in cost savings, but face mask use would remain cost-effective when achieving 90% coverage by July 1, 2022 (ICER \$8293 per QALY) and would remain cost-effective, increasing the ICER to \$36 092 per QALY, when further increasing this cost to \$1.17. As another example, when increasing this cost to \$1.25 per person per day, face masks would remain cost saving for most scenarios and would be cost-effective (ICER \$36 092 per QALY) when achieving a 90% coverage by July 1, 2022 (70% vaccine efficacy; $R_0=5$). When increasing the cost to \$1.39 per person per day, maintaining face masks remained cost saving (appendix p 8) and would be cost-effective if achieving 80% coverage by July 1, 2022 (ICERs $\leq$ \$32 319 per QALY) and when achieving a

90% coverage by May 1, 2022 (ICERs $\leq \$43\,161$ per QALY). However, when face masks cost \$1.39 per person per day, maintaining use would not be cost-effective (ICER \$63 891 per QALY) if achieving 90% coverage by July 1, 2022 (appendix).

Further stratifying the population by age groups increased the number of infections and thus the impact and value of face mask wearing. For example, when achieving 70% vaccination coverage by May 1, 2022 (70% vaccine efficacy; $R_0=5$), maintaining face mask use (18% effectiveness) until then would save \$81.6 billion (78.7–84.5) in societal costs and \$11.2 billion (11.1–11.3) in third-party payer costs, averting 29.8 million (29.6–30.2) cases and 668 400 (661 000–675 900) hospital admissions and treatment, saving 871 600 (838 700–904 600) QALYs.

Increasing the percentage of symptomatic individuals who remain isolated throughout their infectious period did reduce the value of face masks to some degree. However, even when assuming that 100% of people who were infectious and symptomatic stayed isolated, face mask use would still be cost saving, saving \$359.7 million (–12.8 to 732.2) in societal costs and \$575.9 million (503 to 648) in third-party payer costs, averting 1.62 million cases (1.56 to 1.67) and 3950 deaths (3800 to 4100; mask cost \$0.32 per person per day; 50% vaccine efficacy; 70% vaccination coverage by March 1, 2022; $R_0=5$). The only time it would not be cost-effective would be when achieving 90% coverage by Jan 1, 2022, and when vaccine efficacy is at least 70% or face mask costs more than \$0.50 per person per day.

Discussion

The results of this study re-emphasise that vaccination alone is not enough to control the pandemic and prevent deaths and suffering, as well as the importance of multilayered interventions. As has been described previously, each available intervention has different limitations.^{43–45} Combining several layers of interventions can not only cover up these gaps but also further enhance each layer.^{46–48} Our study shows that face mask use can be cost-effective and, in many cases, cost saving, meaning that face mask use would pay for itself. This finding provides strong support for governments, third-party payers, and other organisations to provide face masks to the general public. Moreover, our study showed face mask use should not end as soon as certain amounts of vaccination coverage are achieved, even if these coverages exceed herd-immunity thresholds (eg, ranging from 60% for an R_0 of 2.5 and 90% for an R_0 of 10). That is because virus transmission does not immediately stop once such coverage levels are reached. Instead, face mask use could prevent additional COVID-19 cases until transmission eventually subsides after 2–10 weeks. Our study suggests that there are clear, finite times during which people should continue masking.

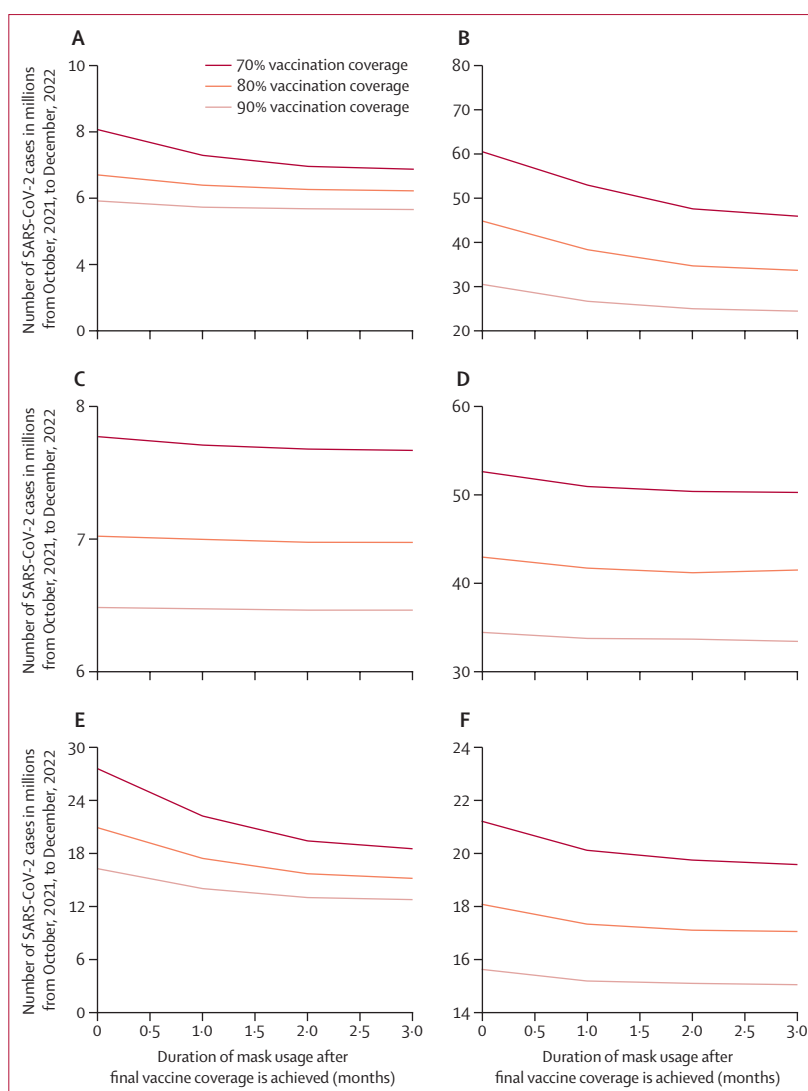


Figure 3: Simulated number of SARS-CoV-2 cases when face masks are used for different durations after the final vaccination coverage is achieved

(A) 70% vaccine efficacy with SARS-CoV-2 $R_0=5$, and vaccination coverage achieved by Jan 1, 2022. (B) 70% vaccine efficacy with SARS-CoV-2 $R_0=8$, and vaccination coverage achieved by Jan 1, 2022. (C) 70% vaccine efficacy with SARS-CoV-2 $R_0=5$, and vaccination coverage achieved by March 1, 2022. (D) 70% vaccine efficacy with SARS-CoV-2 $R_0=8$, and vaccination coverage achieved by March 1, 2022. (E) 50% vaccine efficacy with SARS-CoV-2 $R_0=5$, and vaccination coverage achieved by Jan 1, 2022. (F) 50% vaccine efficacy with SARS-CoV-2 $R_0=5$, and vaccination coverage achieved by March 1, 2022. Maintaining face mask use for longer provided more benefits with lower vaccine efficacies and with increases in R_0 . Note the differences in scales across the panels, which was done to more readily see when outcomes levelled off with increases in the time face masks were used.

The continuing uncertainty of the pandemic further increases face masks' value. Decreasing vaccine effectiveness, as has been the case with waning immunity and the emergence of new variants, only increases the value of face mask wearing. This is the case with increasing transmissibility of the virus, which has been seen with the omicron and delta variants and the current winter surge. Such may be the case in outbreak situations too if vaccine efficacy is lower and transmissibility is higher.

Our experiments also show the value of face mask wearing even as other interventions might change. For example, even if every person who is symptomatic from COVID-19 were to isolate themselves for the full duration of their infectious stage, face mask wearing would still be cost-effective and close to cost saving (eg, when face masks cost $\leq$ US\$0.50 and last 2 days). Such a scenario would not be very realistic given that many people do not get tested for COVID-19 or might not remain isolated throughout their infectious period.^{49–53} This finding demonstrates that although increasing testing might be helpful, it alone will not be enough to control the pandemic and will not remove the need for face mask wearing.

Additionally, our study supports face mask use across the population and not just among specific age groups or in people who have particular mixing patterns. In fact, the more we substratified the population and made mixing patterns heterogeneous, the more the value of face masks increased. This increase in value is caused by the fact that more intense mixing occurs among certain population strata, increasing transmission of the virus and the number of COVID-19 cases.

Our study also estimates the value of increasing face mask effectiveness and adherence. When increasing face mask effectiveness by 10% (implying mask compliance is 44.2%), the relative reduction in cases is greater, with a 17–20% reduction in cases, hospital admissions and treatment, and deaths. Nevertheless, even if there are shortages in more effective face masks (eg, N95 masks), wearing any face mask (eg, cloth masks) is better than not wearing one. This is because people who are infected with SARS-CoV-2 are less likely to transmit the virus to others when wearing a mask, even if it is made of cloth.²⁵

Although our model represented the USA, our results could be applicable to other country settings. The value of face mask wearing was robust to changes in mixing patterns, vaccination coverage, vaccine efficacies, and transmission parameters, which covers a lot of the diversity seen across the world including in low-income and middle-income countries. For example, the 50% vaccine efficacy scenarios are similar to countries primarily using inactivated-virus vaccines,⁵⁴ such as Bahrain, Chile, and Hungary⁵⁵ and the 80% vaccination coverage with 70% vaccine efficacy scenario is similar to current situations in Spain and Australia.⁵⁶ These results can help provide a general estimate for how long after reaching different coverage levels masks can still provide value.

All models, by definition, are simplifications of real life and cannot account for every possible outcome.⁵⁷ Model inputs drew from various sources and time points during the pandemic, and new data on SARS-CoV-2 continues to emerge. We did not vary the effectiveness of face masks on the transmissibility of the virus over the duration of the simulation, however this effectiveness might vary from day to day and over time and with state-level and local-level policies.^{58–60} Our scenarios assume coverage of

the entire population; however, some populations are not yet eligible for vaccination (eg, children aged <5 years). We attempted to be conservative in estimating the value of face masks. For example, we did not include all costs face masks can avert, such as caregiver-productivity losses or declines in economic activity (eg, job loss) nor did we consider QALY losses that could occur during quarantine or isolation (eg, mental health declines or worry of hospital admission and treatment). Incorporating these would further increase the value of wearing face masks.

This study helps quantify the value of maintaining face mask use until certain vaccination coverages are achieved and how doing so can be not just cost-effective, but even cost saving under a wide variety of circumstances. We found substantial value in continuing face mask wearing 2–10 weeks beyond the achievement of target vaccination coverage thresholds to reduce residual SAR-CoV-2 transmission. The emergence of the omicron variant and the prospect of future variants that might be more transmissible and reduce vaccine effectiveness only increases the value of face masks.

Contributors

All authors conceived and designed the question, model, and experiments. All authors collected, accessed, and verified the data. SMB, KJO, KLC, PTW, MCF, SSS, and SNC developed the model. SMB, KJO, MCF, MEB, US, KLC, SNC, PTW, PJH, and BYL parameterised the model. All authors analysed the data. SMB, KJO, MCF, MEB, US, KLC, PTW, SNC, PJH, and BYL helped draft the paper. All authors edited the paper and were included in the decision to submit for publication.

Declaration of interests

PJH and MEB codirect the Texas Children's Center for Vaccine Development and with US are codevelopers of vaccines against emerging and neglected diseases including coronaviruses such as COVID-19. Baylor College of Medicine non-exclusively licensed a COVID-19 vaccine construct to Biological E, an India-based manufacturing company. These authors have no financial stakes in any COVID-19 vaccine candidates under development. All other authors declare no competing interests.

Data sharing

All relevant data are contained within the manuscript text and appendix.

Acknowledgments

This work was supported by the Agency for Healthcare Research and Quality (AHRQ) via grant 1R01HS028165-01, the National Institute of General Medical Sciences as part of the Models of Infectious Disease Agent Study network under grants R01GM127512 and 3R01GM127512-01A1S1, and by the National Science Foundation proposal number 2054858, the National Center for Advancing Translational Sciences of the National Institutes of Health via award number U54TR004279, and by the City University of New York (CUNY) in support of the Pandemic Response Institute (PRI). Statements in the manuscript do not necessarily represent the official views of, or imply endorsement by, the National Institute of Health, AHRQ, the US Department of Health and Human Services, CUNY, or the PRI.

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