Quantifying the effect of delaying the second COVID-19 vaccine dose in England: a mathematical modelling study


Summary

Background The UK was the first country to start national COVID-19 vaccination programmes, initially administering doses 3 weeks apart. However, early evidence of high vaccine effectiveness after the first dose and the emergence of the SARS-CoV-2 alpha variant prompted the UK to extend the interval between doses to 12 weeks. In this study, we aimed to quantify the effect of delaying the second vaccine dose in England.

Methods We used a previously described model of SARS-CoV-2 transmission, calibrated to COVID-19 surveillance data from England, including hospital admissions, hospital occupancy, seroprevalence data, and population-level PCR testing data, using a Bayesian evidence-synthesis framework. We modelled and compared the epidemic trajectory in the counterfactual scenario in which vaccine doses were administered 3 weeks apart against the real reported vaccine roll-out schedule of 12 weeks. We estimated and compared the resulting numbers of daily infections, hospital admissions, and deaths. In sensitivity analyses, we investigated scenarios spanning a range of vaccine effectiveness and waning assumptions.

Findings In the period from Dec 8, 2020, to Sept 13, 2021, the number of individuals who received a first vaccine dose was higher under the 12-week strategy than the 3-week strategy. For this period, we estimated that delaying the interval between the first and second COVID-19 vaccine doses from 3 to 12 weeks averted a median (calculated as the median of the posterior sample) of 58 000 COVID-19 hospital admissions (291 000 cumulative hospitalisations [95% credible interval 275 000–319 000] under the 3-week strategy vs 233 000 [229 000–238 000] under the 12-week strategy) and 10 000 deaths (64 800 deaths [60 000–68 900] vs 54 700 [52 800–55 600]). Similarly, we estimated that the 3-week strategy would have resulted in more infections compared with the 12-week strategy. Across all sensitivity analyses the 3-week strategy resulted in a greater number of hospital admissions. In results by age group, the 12-week strategy led to more hospitalisations and deaths in older people in spring 2021, but fewer following the emergence of the delta variant during summer 2021.

Interpretation England’s delayed-second-dose vaccination strategy was informed by early real-world data on vaccine effectiveness in the context of limited vaccine supplies in a growing epidemic. Our study shows that rapidly providing partial (single-dose) vaccine-induced protection to a larger proportion of the population was successful in reducing the burden of COVID-19 hospitalisations and deaths overall.

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Introduction

The Pfizer–BioNTech COVID-19 vaccine BNT162b2 (tozinameran) and Oxford–AstraZeneca COVID-19 vaccine ChAdOx1 nCoV-19 were approved on Dec 2 and Dec 30, 2020, respectively, in the UK, making the UK the first country to start nationwide COVID-19 vaccination.1,2 Vaccines were prioritised for those most at risk of developing severe COVID-19. People residing in care homes and their carers were vaccinated first. Vaccination then proceeded in descending 5-year age groups, also accounting for pre-existing clinical conditions. Initially, the two scheduled doses of each vaccine were administered 3–4 weeks apart, similar to the schedule used in clinical trials. However, the Joint Committee on Vaccination and Immunisation (JCVI) later recommended delaying the second dose from 3 to 12 weeks after the first dose,3 on the basis of evidence that one vaccine dose provided 70–90% protection against symptomatic disease4 and that a higher antibody peak was observed in individuals who received a delayed second dose compared with those who received their second dose at 3 weeks.5 The delayed-second-dose strategy allowed the delivery of more first vaccine doses to be prioritised and, thus, high short-term partial
protection for as many people as possible, which was important in the context of the SARS-CoV-2 alpha (B.1.1.7) variant of concern emerging at the time.

This strategy received criticism, citing the lower protection offered to people at highest risk from the disease by delaying the second dose, the limited evidence to support this change from trial protocols, and concerns of partial vaccination accelerating the emergence of vaccine-evading variants of concern.6,7 However, prompted by vaccine shortages and the emergence of vaccine-evading variants of concern,6,7 several countries, including Canada,8 Denmark,9 Norway,10 India,11 and South Africa,12 also extended the time between doses. Previous studies have explored the potential impact and optimisation of mass vaccination schedules under different assumptions regarding vaccine effectiveness, vaccine mode of action, waning immunity, and use of non-pharmaceutical interventions.13 These studies showed that more hospitalisations and deaths could be prevented under a delayed-second-dose strategy, but results were sensitive to vaccine effectiveness assumptions and vaccine mechanisms, underscoring the importance of continued non-pharmaceutical interventions.13-15 Quantifying the effect of interventions is crucial to evaluating the success of an epidemic response, allowing decision makers to improve and inform ongoing and future interventions.

The aims of the current study were to retrospectively assess the effect of delaying the second vaccine dose in England and to examine what the epidemic trajectory in terms of COVID-19 hospitalisations, deaths, and SARS-CoV-2 infections would have looked like if a 3-week interval had been maintained.

Methods

Study population and data sources
We used data on daily COVID-19 hospital admissions, bed occupancy, deaths, and positive and negative PCR test results for individuals aged 25 years or older in each of the seven National Health Service (NHS) regions in England. All data were collected by the UK Government’s Department of Health and Social Care as part of surveillance activities and were shared with us or are publicly available. Population-level data on the prevalence of positive PCR tests from the Real-time Assessment of Community Transmission (REACT) study,18 prevalence of SARS-CoV-2 antibody positivity based on serological data, the daily number of SARS-CoV-2 variant tests identified as delta (B.1.617.2) or non-delta in the variant mutation dataset from the UK Health Security Agency, and the daily number of first and second vaccine doses received by age and vaccine type, as reported by the NHS, were also aggregated at the NHS regional level. All data were fully anonymised, and some were further aggregated for statistical disclosure purposes (appendix 1 p 5).

Ethics permission was sought for the study through the standard ethical review processes of Imperial College London (London, UK), and was approved by the university’s research governance and integrity team (Imperial College Research Ethics Committee reference 21IC6945). Patient consent was not required as the
research team accessed fully anonymised data only, which were collected as part of routine public health surveillance activities by the UK Government.

**Epidemiological model and fitting**

We used a previously described susceptible–exposed–infectious–removed stochastic transmission model\(^{19}\) which reliably captures the age-specific scale and timing of the SARS-CoV-2 pandemic in England in 2021\(^{20}\) to examine the effect of vaccination between Dec 8, 2020, when vaccination started, and Sept 13, 2021, just before the introduction of booster doses in England, which are not considered in this study (figure 1). This period was marked by the transition (in May–June, 2021) from alpha to delta as the dominant SARS-CoV-2 variant in the UK population.

We modelled the population by English NHS region and by 5-year age bands (from 0–4 years to 75–79 years), with a single category for people aged 80 years and older, a category for care-home workers, and a category for care-home residents.\(^{19}\) We represented individuals according to their infection status, modelling infected individuals in the community and in hospitals, with detailed clinical pathways, vaccination status, and SARS-CoV-2 variants (figure 1; appendix 1 p 4). We fit a two-variant model to multiple data sources for each NHS region (appendix 1 pp 47–48), explicitly capturing the emergence of the delta variant (appendix 1 p 48). The delta variant is seeded at a region-specific date determined by the model fit. We used Bayesian evidence synthesis inference, allowing all data sources to jointly inform the model in a single robust statistical framework\(^{21}\) and examined daily and cumulative infections, hospital admissions, and deaths. Further methodological detail is available in appendix 1 (pp 3–39).

We modelled vaccine roll-out, including dosing interval, as reported by the NHS. Thus, the actual average dosing interval might differ slightly from reported guidelines. We refer to this as the 12-week strategy.

Vaccine effectiveness against infection, symptomatic disease, hospitalisation, death, and onward transmission for each variant was informed by UK-based effectiveness studies.\(^{22,24}\) We assumed the first dose to be effective 21 days after administration, with no protection beforehand, and the second dose to reach full effectiveness 7 days after administration, with a stepwise change in the individual vaccine protection at these changepoints (appendix 1 p 8). Our baseline analysis assumes the same vaccine effectiveness under the 12-week and 3-week strategies and no waning after the first dose, regardless of dosing interval.

However, we allowed for waning of infection-induced protection and vaccine-induced protection (after the second dose only), imperfect cross-protection between variants, and a fitted increased severity of the delta variant relative to the alpha variant.\(^{25}\) We assumed that infection-induced immunity against the same SARS-CoV-2 variant wanes following an exponentially distributed duration with a mean of 6 years.\(^{7}\) To model waning of vaccine-induced protection, we assumed individuals who had received two vaccine doses moved to a reduced-protection (ie, waned) compartment after, on average, 24 weeks. We fitted vaccine effectiveness in the second-dose and reduced-protection compartments, for all vaccines and disease outcomes, to the time-varying vaccine effectiveness previously estimated by Andrews and colleagues\(^{21,24}\) (figure 2; appendix 1 pp 11–13).

**Assessing the potential effect of alternative vaccination schedules**

We explored a counterfactual scenario with a 3-week interval between doses (referred to as the 3-week strategy) to assess the effect of increasing the vaccine dosing interval to 12 weeks (12-week strategy) on the epidemic trajectory. To account for the limited vaccine supply, we assumed that the total (first and second dose) daily number of vaccines administered matched that reported by the NHS. Doses were then distributed between first and second doses according to the dosing interval in the respective scenario (figure 3A). We compared the reported numbers and age distribution of hospital admissions between the fitted 12-week strategy and the counterfactual 3-week strategy.
We estimated the time-varying transmission rate ($\beta$) by fitting the model to data up to Sept 13, 2021, capturing the effect of changing restrictions and behaviours (appendix 1 pp 36–37, 49; appendix 2), and used these estimated $\beta$ values to simulate the 3-week strategy.

**Sensitivity analyses**

We ran sensitivity analyses to assess the effect of assumptions on vaccine effectiveness and waning of vaccine-induced protection on our results (appendix 1 p 40). First, we accounted for uncertainty in vaccine effectiveness when a 3-week interval is assumed. Second, to account for general uncertainty in vaccine effectiveness against the delta variant, we ran analyses for a range of vaccine effectiveness values. Third, we considered uncertainty in the waning of vaccine-induced immunity by running analyses with varying vaccine effectiveness in the reduced-protection compartment after the second dose. Fourth, we accounted for uncertainty in the timing of vaccine-induced waning immunity by testing a longer mean waning time, considering that the shorter (3-week) dosing interval might affect the mean duration of waning after the second dose. Fifth, we considered uncertainty in the waning of immunity following the first dose. As waning of vaccine effectiveness after the first dose is not explicitly modelled, the first-dose vaccine effectiveness values used represent the mean vaccine effectiveness afforded across the 12 weeks between doses. A shorter dosing interval could plausibly increase the mean vaccine effectiveness after the first dose because of reduced waning after the first dose. Thus, we considered a scenario in which first-dose vaccine effectiveness was increased in the 3-week interval counterfactually. Finally, we assessed the potential effect of immediate vaccine-induced protection after the first dose as an extreme assumption on time to effectiveness.

In two simple exploratory analyses, we considered longer-term SARS-CoV-2 dynamics beyond the end of the study period based on extreme scenarios (appendix 1 pp 65–67).

Analyses were conducted in R version 4.1.0 (see appendix 1 p 46 for full details of package versions).

**Role of the funding source**

The funders of this study had no role in the study design, data collection, data analysis, data interpretation, or writing of the report.

**Results**

From Dec 8, 2020, to Sept 13, 2021, use of the 12-week interval between first and second doses adopted in the UK led to a greater number of individuals receiving their first vaccine doses than would have been possible using the 3-week interval. As of Sept 13, 2021, 40410555 first doses were administered with use of the 12-week interval, compared with 38962837 first doses administered in the counterfactual 3-week scenario. With a 3-week interval between doses, fewer individuals would receive their first vaccine dose, but the roll-out of second doses would start sooner for individuals identified as being at highest risk of severe disease (ie, the oldest individuals and those living in care homes; figure 3A).

Our model effectively captures national COVID-19 daily hospital admissions by age in our study period (figure 3B; appendix 1 p 47). The 3-week strategy led to a higher peak number of daily hospital admissions during the delta variant wave, with 2030 hospitalisations (95% credible interval 1690–2360) on July 22, 2021, in our baseline

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**Figure 2: Vaccine effectiveness against the SARS-CoV-2 delta variant over time following the second dose of COVID-19 vaccine**

Vaccine effectiveness is shown separately for the Oxford–AstraZeneca vaccine (ChAdOx1 nCoV-19; left column) and the Pfizer–BioNTech vaccine (BNT162b2, tozinameran; right column), and for three outcomes: death (A), severe disease (B), and mild disease or infection (C). We assumed the same protection against infection and mild disease. The graphs show data and uncertainty ranges representing vaccine effectiveness estimates from Andrews and colleagues’ study, and points corresponding to our model assumptions. We assumed that the Moderna vaccine has the same vaccine effectiveness as BNT162b2. Note: the x-axis differs in the bottom row. Corresponding data for the SARS-CoV-2 alpha variant are provided in appendix 1 (p 13).
scenario (compared with the observed 827 hospitalisations in the 12-week scenario; figure 3B). Under the 3-week strategy, we estimated 291,000 (275,000–319,000) cumulative hospitalisations and 64,800 (60,200–68,900) deaths between Dec 8, 2020, and Sept 13, 2021, compared with 233,000 (229,000–238,000) hospitalisations (figure 3C) and 54,700 (52,800–55,600) deaths under the 12-week strategy over the same period. Additionally, more infections occurred under the 3-week (16,400,000 [15,200,000–19,200,000]) than the 12-week strategy (12,700,000 [11,100,000–16,000,000]; appendix 1 p 70).

Cumulative COVID-19 hospitalisations were greater under the 3-week than the 12-week strategy up to Sept 13, 2021 (figure 3C), with a more apparent difference between strategies from late May, 2021, following the emergence of the delta variant. This difference stabilised in September as, under the 3-week strategy, the epidemic peaked and then declined much faster than in the observed 12-week strategy because of rapid depletion of the number of susceptible individuals.

The greater number of hospitalisations estimated under the counterfactual 3-week strategy was driven by fewer individuals overall benefiting from full or partial vaccine-induced protection. For example, by early April 2021, 7·7 million fewer individuals had any level (one or two doses) of vaccine-induced protection under the 3-week than the 12-week strategy. This pattern persisted in April and May, 2021 (figure 4A), and the gap subsequently narrowed from June, 2021, onwards.

The number of individuals with reduced protection after the second dose was higher throughout the study period under the 3-week than the 12-week strategy: vaccine protection under the 3-week strategy had already started to wane in some individuals by March, 2021 (appendix 1 p 55). This number increased over time, with 10 million people under the 3-week and 7 million under the 12-week strategy having reached at least 24 weeks post second dose by the beginning of July, 2021 (appendix 1 p 56). This consistently higher level of reduced protection in the 3-week strategy was due to the prioritisation of fully vaccinating (with second doses) each eligible age group before the next group became eligible (appendix 1 p 14).

Throughout the study period, we found a lower proportion of individuals at risk of infection at each timepoint (figure 4B) and from June, 2021 onwards a lower risk, through vaccination, of hospitalisation if infected (figure 4C) in the 12-week than the 3-week vaccination strategy. In the 3-week strategy, although the oldest age groups (at highest risk of severe disease) received greater protection earlier, the population-level risk of severity was still higher than in the 12-week strategy (figure 4C).

We estimated the age distribution of hospitalisations to remain broadly similar under both vaccination strategies (appendix 1 p 56), with most hospitalisations in the older age groups (figure 5).

During the study period, the 12-week strategy led to more individuals being partially protected for longer
before their second dose was effective, reflected in a small proportion of older individuals in this category (>21 days post first dose; figure 5) being hospitalised during that period. Conversely, under the 3-week strategy, there were almost no hospitalisations among individuals with partial protection from a single vaccine dose. However, this short-term benefit of the 3-week strategy was rapidly lost, with many more hospitalisations occurring in the summer of 2021 under the 3-week than the 12-week strategy (figure 5).

These trends were observed regardless of age group. Across both strategies, the individuals at highest risk of severe disease (those aged >80 years) were vaccinated first. The 3-week strategy, however, gave higher protection most quickly for those at highest risk. Thus, by the peak of the delta variant wave, vaccine-induced protection in these individuals who received their last vaccine dose at least 6 months ago would have decreased, making them susceptible again to severe outcomes (appendix 1 p 56). For example, by Sept 13, 2021, we estimated that 2.8 million individuals aged 75 years and older had received their vaccine more than 24 weeks ago under the 12-week strategy, compared with 3.3 million under the 3-week strategy. Prioritising fully vaccinating the population at highest risk as quickly as possible under the 3-week strategy would have reduced the short-term morbidity and mortality in the older age groups but increased the total long-term burden because of waning vaccine-induced protection and higher levels of virus circulating in younger age groups who drive transmission.

Across all sensitivity analyses, including a scenario assuming no waning of vaccine-induced protection, we found that the 3-week strategy led to more partially protected individuals which temporarily led to more hospitalisations. For example, by Sept 13, 2021, we estimated that 2.8 million individuals aged 75 years and older had received their vaccine more than 24 weeks ago under the 12-week strategy, compared with 3.3 million under the 3-week strategy. Prioritising fully vaccinating the population at highest risk as quickly as possible under the 3-week strategy would have reduced the short-term morbidity and mortality in the older age groups but increased the total long-term burden because of waning vaccine-induced protection and higher levels of virus circulating in younger age groups who drive transmission.

Across all sensitivity analyses, including a scenario assuming no waning of vaccine-induced protection, we found that the 3-week strategy led to a greater number of hospitalisations and deaths than the 12-week strategy within the study period (appendix 1 pp 57–64, 68–69). In addition, in two exploratory analyses that looked beyond the end of the study period, we showed that the benefits of the 12-week strategy persisted beyond Sept 13, 2021, at least up to the start of February, 2022 (appendix 1 pp 65–67).

**Discussion**

Our study explored the effect of the strategy of delaying the interval between COVID-19 vaccine doses to 12 weeks in England between Dec 8, 2020, and Sept 13, 2021, comparing the observed number of hospitalisations and deaths to a counterfactual scenario in which the vaccine dose interval remained 3 weeks, as in clinical trials. We estimated in our baseline scenario that delaying the interval between the first and second COVID-19 doses from 3 to 12 weeks averted a median 58,000 hospitalisations in England by Sept 13, 2021, and averted between 39,000 and 211,000 total hospitalisations across all sensitivity analyses.

The 12-week strategy led to more partially protected individuals which temporarily led to more hospitalisations...
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and deaths in older individuals in spring 2021 (figure 5; appendix 1 p 70). However, the strategy provided partial (single-dose) protection to more age groups, including younger groups that might sustain transmission, which indirectly protected those at high risk. Conversely, prioritising fully vaccinating the people at highest risk with two doses under the 3-week strategy led to a large proportion of the population at highest risk having a lower level of vaccine-induced immunity during the delta variant wave in summer 2021 due to waning immunity, which resulted in higher peak hospitalisations. The magnitude of the effect of the 12-week strategy might also be sensitive to the timing of the delta variant wave. Had the delta variant emerged 3 months later, the 12-week strategy would probably have still been more beneficial than the 3-week strategy, but to a smaller relative extent within the short-to-medium-term COVID-19 epidemic dynamics considered here.

Retrospective assessments of the effects of different vaccination strategies in other countries are not yet available. However, our findings are consistent with previous prospective simulation studies which also found that prioritising partial protection of a larger proportion of the population by increasing the dosing interval could reduce hospitalisations and deaths. Barnpounakis and colleagues found that the optimal strategy was to prioritise fully vaccinating the oldest individuals before switching to a delayed-second-dose strategy for those younger than 75 years. This is not far from the strategy that England pursued, with around 25% of people aged 80 years or older being vaccinated with a first dose before the JCVI changed their guidance. This combined strategy essentially targets a combination of susceptibility to severe disease in the highest risk groups and infectivity in the younger age groups.

Mathematical models are valuable tools to quantitatively evaluate vaccination programmes, improve their design, and monitor new vaccine initiatives. By using a Bayesian evidence-synthesis approach, we integrated multiple data sources to capture the epidemic in England accurately. By explicitly accounting for the introduction of variants of concern, vaccine endpoints, and the waning of immunity, we robustly explored the effects of alternative vaccination strategies and a wide range of sensitivity analyses.

Our study has limitations. First, there is substantial uncertainty in vaccine effectiveness by dosing interval.
UK studies are limited because of the early switch in strategy.

Studies in countries where a 3-week switch maintains suggest that vaccine effectiveness is slightly lower compared with a 12-week interval, a hypothesis that we explored in a sensitivity analysis with findings similar to those of our main analysis. Second, we assumed a simple model of waning immunity with only two stages. However, sensitivity analyses varying assumptions about waning vaccine-induced protection produced results consistent with our main analysis. Third, we did not directly account for waning of vaccine-induced immunity after the first dose. Studies have estimated that protection starts to wane from 4–5 weeks after the first dose in some age groups, but with large uncertainty. According to our sensitivity analyses, such waning after the first dose did not alter our results.

Fourth, although we capture temporal changes in population contact rates, we assumed that, under the 3-week strategy, mixing patterns (ie, $\beta$ transmissibility values) remained identical to those estimated under the 12-week strategy. It is possible that, under a 3-week strategy, the final step of the roadmap (in which non-pharmaceutical interventions in the UK were lifted in a controlled stepwise manner) would have been delayed further as the projected hospitalisations would have been much higher (figure 3B): behaviours might also have been different under that strategy. Therefore, our counterfactual analysis can only represent a scenario assuming only the vaccination interval changed. Fifth, we assumed the same vaccination rate for all analyses as reported in the NHS data. With more doses administered per day, the 12-week delay might not have been optimal. Sixth, we did not consider the potentially reduced risk of emergence of a variant of concern in the 3-week compared with the 12-week strategy. However, with SARS-CoV-2 circulating globally, and most variants of concern rapidly spreading worldwide, a change in the risk of emergence in England alone is unlikely to have affected the broader patterns of emergence and therefore the circulation of variants.

Finally, although we have quantified the relative success of the 12-week versus the 3-week strategy in terms of COVID-19 hospitalisations and deaths, and SARS-CoV-2 infections in the first 9 months of the vaccination programme, we have only considered longer-term SARS-CoV-2 dynamics in two simple exploratory analyses (appendix 1 pp 65–67), which did not account for either booster and further vaccine doses or novel variants. Our work, therefore, does not fully explore the potential effect of the delayed-second-dose strategy on future epidemic waves. We also did not consider the long-term burden of disease, such as post-COVID-19 condition (also known as long COVID), although this is likely to be proportional to the infection burden. Furthermore, we did not account for geographical or socioeconomic factors that can affect SARS-CoV-2 transmission rates and outcomes, and did not conduct analyses by sex or ethnicity, which would require granular individual-level data not considered in this study. Therefore, our results should be interpreted as the population-level average effects at the NHS regional level, and not at higher resolution.

Our study shows that early and continuous assessment of real-world vaccine effectiveness is crucial, especially in emergency situations. There can be benefit in carefully considering and adapting guidelines in light of new emerging evidence and the population in question. Our results could also help to quantitatively inform lessons-learned exercises, such as the UK Government’s ongoing COVID-19 inquiry.

Our findings might also be useful for other countries considering different vaccination intervals for future booster campaigns or in preparation for future waves of COVID-19. However, it is difficult to extrapolate findings from England to other settings because of differences in demography, behaviours, implementation of non-pharmaceutical interventions, availability of vaccines, and variants of concern in circulation. Additional retrospective studies from multiple countries with differing non-pharmaceutical interventions and variants will help to build a body of evidence regarding optimal vaccination strategies. However, across all sensitivity analyses explored, we estimated that, in England, the switch to a delayed vaccine interval was beneficial in the short to medium term. Importantly, this beneficial effect is observed across all age groups, including those at highest risk, who had higher indirect protection under the 12-week strategy.

It was fortunate that both vaccines licensed in England were highly effective, combined with a high uptake of both doses despite the longer dosing interval. In other settings where vaccine supply is limited, or where vaccines with lower effectiveness are widely used, a switch to a 12-week strategy might not be advantageous. Therefore, it is crucial to consider the likely acceptance of new vaccines or doses and the potential barriers to uptake, especially during periods of sustained high transmission when vaccine-evading variants might emerge. Models have shown that long-term COVID-19 dynamics are strongly shaped by vaccination policies with wide-ranging epidemiological and evolutionary outcomes. Therefore, as further vaccine doses are rolled out, it will be important to continue evaluating vaccine effectiveness against any new variants and waning vaccine-induced protection.

Beyond the immediate priority of COVID-19, understanding the effect that changing COVID-19 vaccination guidance has had or might have on hesitancy towards other vaccines or on overall trust in public health guidance is crucial.

Contributors
NI, TR, NM, ACG, MB, and AC conceived the study. NI and TR analysed the data, created the figures, and wrote the original draft of the manuscript. TR, LKW, RS, RGF, ESR, YE, DTK, PNP-G, MB, and AC...
developed the code base. All authors contributed to interpretation, investigation, and reviewing and editing of the manuscript. WH, KAMG, N, HW, RAD, KF, ESK, and PNP-G accessed and verified the underlying data used in the study.

Declaration of interests
AC has received payment from Pfizer for teaching of mathematical modelling of infectious diseases. KAMG has received honoraria from Wellcome Genome Campus for lectures. LWK has received consultancy payments from the Wellcome Trust. ABH has received consultancy payments from WHO for COVID-19-related work; provides advice on COVID-19 modelling to the New South Wales Ministry of Health, Australia; and was previously engaged by Pfizer to advise on modelling of RSV vaccination strategies, for which she received no financial compensation. RS and NI are currently employed by the Wellcome Trust. All other authors declare no competing interests.

Data sharing
All code, scripts, and data used to produce the results in this Article are available online at GitHub. Data sharing

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For the GitHub repository related to this study see: https://github.com/mrc-ide/sarscov2-vaccine-delay
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