

# Indirect Protection by Reducing Transmission: Ending the Pandemic With Severe Acute Respiratory Syndrome Coronavirus 2 Vaccination

Aaron Richterman,<sup>1</sup> Eric A Meyerowitz,<sup>2</sup> and Muge Cevik<sup>3</sup>

<sup>1</sup>Division of Infectious Diseases, Hospital of the University of Pennsylvania, Philadelphia, Pennsylvania, USA, <sup>2</sup>Division of Infectious Diseases, Montefiore Medical Center, Bronx, New York, USA, <sup>3</sup>Division of Infection and Global Health Research, School of Medicine, University of St Andrews, Fife, Scotland, United Kingdom

It is remarkable that, in less than 1 year since the coronavirus disease 2019 (COVID-19) pandemic began, multiple vaccines using a variety of platforms have demonstrated high efficacy for protection against symptomatic COVID-19 in randomized controlled trials. This protection appears to be especially potent against severe COVID-19, with sizable reductions in severe outcomes now being confirmed in real-world settings at a much larger scale [1, 2]. The direct protection against disease measured by the clinical trials is important, but whether and to what extent the vaccines provide indirect protection by reducing transmission is also of great consequence in controlling and eventually ending the pandemic [3]. Therefore, understanding the effects of vaccines on transmission is key to deploying evidence-based population vaccination plans, recommendations for the public, and policies for use of nonpharmaceutical interventions with

varying degrees of effectiveness in this next stage of the pandemic [4].

There are 2 ways a vaccine can reduce transmission risk. First, a vaccine may decrease the probability of a recipient becoming infected in the first place by protecting against both symptomatic (as measured by the primary endpoints of the clinical trials) and asymptomatic infection (which can only be identified using systematic polymerase chain reaction [PCR] or serology testing). Second, a vaccine may decrease the probability of secondary transmission from an infected vaccine recipient by reducing the duration or degree of infectiousness. Accumulating evidence suggests that severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) vaccines can substantially reduce transmission through both of these mechanisms.

## EVIDENCE OF PROTECTION BY VACCINES AGAINST INFECTION: SYMPTOMATIC AND ASYMPTOMATIC

Three randomized controlled trials to date provide evidence supporting protection against all infection (including asymptomatic infection) (Table 1). In the Moderna messenger ribonucleic acid (mRNA)-1273 vaccine trial, all asymptomatic participants underwent PCR testing at the time of the second dose, and the study showed a 61% (95% confidence interval [CI], 31%–79%) reduction in asymptomatic infection relative to an 85% (95% CI, 66%–93%) reduction in

symptomatic infection before the second dose [5]. This is likely to underestimate efficacy against new infection because PCR may remain positive for weeks after infection (and thus testing may include residual positive testing before the effect of the first dose), and the efficacy was assessed before full protection after both doses [6]. The AstraZeneca ChAdOx1 nCoV-19 vaccine was evaluated in a series of pooled trials, one of which included weekly screening by PCR, and showed a 55.7% (95% CI, 41.4%–66.7%) reduction in all infections, relative to a vaccine efficacy against symptomatic disease of 70.4% (95% CI, 54.8%–80.6%) [7]. By using cross-sectional testing, the estimates from these 2 studies are actually composite measures of reduced risk of infection and duration of PCR positivity (ie, duration of infection) [8]. Finally, the randomized controlled trial of the Janssen AD26.COV2.S vaccine included a subset of participants with available serology data at day 71, and it showed a 65.5% (95% CI, 39.9%–81.1%) reduction in all infections after day 29, compared to a 66.5% (95% CI, 55.5%–75.1%) reduction against symptomatic COVID-19 [9]. A limitation of serology-based studies is that there may be a reduced sensitivity for identifying asymptomatic infections [10, 11].

Protection against infection has also been shown in observational studies of healthcare workers, community members, patients, and elderly residents of long-term care facilities. These studies

Received 29 March 2021; editorial decision 13 May 2021; accepted 14 May 2021.

Correspondence: Aaron Richterman, MD, 3400 Spruce Street, Philadelphia, PA 19104, USA (aaron.richterman@penmedicine.upenn.edu).

Open Forum Infectious Diseases® 2022

© The Author(s) 2021. Published by Oxford University Press on behalf of Infectious Diseases Society of America. This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs licence (<http://creativecommons.org/licenses/by-nc-nd/4.0/>), which permits non-commercial reproduction and distribution of the work, in any medium, provided the original work is not altered or transformed in any way, and that the work is properly cited. For commercial re-use, please contact journals.permissions@oup.com 10.1093/ofid/ofab259

**Table 1. Effect of Vaccination on Total SARS-CoV-2 Infection Risk**

Vaccine	Sample Size	Setting	Vaccine Efficacy/Effectiveness
<b>Randomized Controlled Trials</b>			
mRNA-1273 [5]	30 420	United States	61% (95% CI 31–79%) reduction in asymptomatic infection prior to second dose (15 cases vs. 39 cases) relative to 85% reduction (95% CI 66–93%) in symptomatic infection
ChAdOx1 nCoV-19 [7]	3744 (subgroup)	England and Wales	55.7% (95% CI 41.4–66.7%) reduction in all infections (68 vs. 153 cases) relative to 70.4% reduction (95% CI 54.8–80.6%) in symptomatic infection
AD26.COV2.S [9]	2650 (subgroup)	Argentina, Brazil, Chile, Colombia, Mexico, Peru, South Africa, and the United States	65.5% (95% CI 39.9–81.1%) reduction in asymptomatic infections (18 vs. 50 cases) relative to 66.5% reduction (95% CI 55.5–75.1%) in symptomatic infection
<b>Observational Studies with Control of Confounding</b>			
BNT162b2 [12]	23 324	Healthcare workers in UK	85% reduction (95% CI 74–96%) in all SARS-CoV-2 infections 7 days after 2nd dose
mRNA-1273 and BNT162b2 [13]	3975	Healthcare workers, first responders, and frontline workers in the United States	91% reduction (95% CI 76–97%) in all SARS-CoV-2 infections after full vaccination
ChAdOx1 nCoV-19 or BNT162b2 [3]	373 402	Community members in UK	70% reduction (95% CI 62–77%) in all SARS-CoV-2 infections after the second dose
mRNA-1273 or BNT162b2 [15]	39 156	Pre-procedural screening in the United States	80% reduction (95% CI 56–91%) in all positive tests
ChAdOx1 nCoV-19 or BNT162b2 [16]	10 412	Elderly residents of Long-term care facilities in UK	62% reduction (95% CI 23–81%) in all SARS-CoV-2 infections 35 days after the first dose

include regular or systematic PCR testing, compare SARS-CoV-2 infection risk between otherwise similar vaccinated and unvaccinated individuals, and adjust for confounding variables associated with both the probability of receiving a vaccine and exposure to SARS-CoV-2. One such study included over 23 000 healthcare workers in the United Kingdom who underwent SARS-CoV-2 PCR testing at least every 2 weeks (twice per week for frontline healthcare workers) during roll out of the Pfizer-BioNTech BNT162b2 vaccine [12]. After controlling for potential confounders (demographic characteristics, comorbidities, job role, frequency of contact with patients with COVID-19, employment in a patient facing role, and occupational exposure), investigators found that receipt of the vaccine was associated with a 70% reduction (95% CI, 55%–85%) in all SARS-CoV-2 infections 21 days after the first dose and an 85% (95% CI, 74%–96%) reduction 7 days after the second dose. A similar cohort study of 3975 health care workers, first responders, and other frontline workers in the United States who were tested weekly found a 91% reduction (95% CI, 76%–97%) in infection risk after full

vaccination by an mRNA vaccine and an 81% reduction (95% CI, 64%–90%) after partial vaccination after adjusting for propensity to be vaccinated, location, occupation, and local viral circulation [13]. A cohort study of 373 402 community members in the United Kingdom who were regularly tested using SARS-CoV-2 PCR every 1–4 weeks found progressively stronger protection from infection with greater time after either the AstraZeneca ChAdOx1 nCoV-19 or Pfizer-BioNTech BNT162b2 vaccines, peaking with a 70% reduction (95% CI, 62%–77%) after the second dose after adjusting for demographics, neighborhood deprivation, work setting, comorbidity, and household characteristics, among other confounders [14]. Another study evaluated 39 156 consecutive asymptomatic individuals who had preprocedural SARS-CoV-2 PCR screening at a large US healthcare system [15]. After adjusting for demographic characteristics and repeated testing, vaccinated patients had an 80% reduction (95% CI, 56%–91%) in risk of infection after the second dose of either the Pfizer-BioNTech BNT162b2 or the Moderna mRNA-1273 vaccines, with similar protection seen starting 10 days after the first

dose. Vaccine effectiveness against all infections regardless of symptoms has also been shown in long-term care facilities, a particularly high-risk setting that was not considered in clinical trials. A study of 10 412 residents in the United Kingdom with a median age of 86 who had regular PCR screening at least monthly showed a 62% reduction in infection risk (95% CI, 23%–81%) 35 days after the first dose of the Pfizer-BioNTech BNT162b2 or AstraZeneca ChAdOx1 nCoV-19 vaccines after adjusting for sex, age, prior infection, bed capacity, and local SARS-CoV-2 incidence [16]. Although all of these studies attempted to adjust for confounding variables, their findings may still be biased if there are large unmeasured differences in vaccinated and unvaccinated populations. Other vaccine effectiveness studies that included regular PCR screening but did not adjust for potential confounding variables have similarly found strong protection against all infections regardless of symptoms [17–20].

Experimental and observational evidence thus suggests that vaccines across multiple platforms are associated with large reductions in all SARS-CoV-2 infections regardless of symptoms, with

protection that is almost as high as that provided against symptomatic COVID-19. There may be some populations—such as certain immunocompromised individuals—where this is not the case, although limited data suggest protection against at least symptomatic infection is broadly preserved [21]. Another caveat is that, with the exception of the Janssen AD26.COV2.S vaccine, these data were not obtained in the context of the variants currently most concerning for immune escape—Beta, Delta, and Gamma. These variants, and several mutations contained within them, are associated with varying degrees of reduction in neutralizing activity by serum from vaccinated individuals [22–24], although this does not necessarily correlate with loss in clinical protection. It is not yet known to what degree these variants are associated with a clinically meaningful change in vaccine effectiveness against overall infection.

### EVIDENCE OF REDUCED TRANSMISSION POTENTIAL FOR PEOPLE INFECTED AFTER VACCINATION

The decrease in overall SARS-CoV-2 infection risk after vaccination is the lower bound on a vaccine's effect on transmission. There will be additional reductions in transmission risk if infected vaccine recipients have lower transmission potential relative to infected people who have not been vaccinated. It is already known that people with asymptomatic infection have a shorter duration of viral load shedding and lower secondary attack rates, with a meta-analysis finding a secondary

attack rate of 1% (95% CI, 0%–2%) for asymptomatic index cases relative to 7% (95% CI, 3%–11%) for presymptomatic cases and 6% (95% CI, 5%–8%) for symptomatic index cases [25–27]. As a result, even in the absence of a decrease in overall infections with vaccination, the reduction in symptomatic infections demonstrated in the clinical trials is expected to result in sizable attenuation in transmission risk.

The most direct way to assess transmission potential of vaccine recipients who become infected is through epidemiological studies directly measuring secondary attack rates among contacts of infected vaccine recipients (Table 2). In a transmission study of over 550 000 households in England, contacts of index cases who had received the first dose of either the Pfizer-BioNTech BNT162b2 or AstraZeneca ChAdOx1 nCoV-19 vaccine 21 days or more before testing positive were approximately 50% less likely to become infected after adjusting for confounding [28]. This 50% reduction may be an underestimate for 2 reasons. First, contact-tracing studies like this are most likely to identify index cases with greater symptoms, there is evidence that the vaccines reduce severity of symptoms among those who become infected, and those with fewer symptoms have lower secondary attack rates (as discussed below). Second, some contacts may have been infected outside the household.

Although it is not a direct measure of secondary attack rates, a nationwide cohort study in Scotland found that household members of healthcare workers who were at least 14 days after their second

dose of either the Pfizer-BioNTech BNT162b2 or the AstraZeneca ChAdOx1 nCoV-19 vaccine had a 54% reduction in infection risk (95% CI, 50%–70%) relative to household members of unvaccinated healthcare workers after adjusting for demographic characteristics, socioeconomic deprivation, comorbidity, healthcare worker role, occupation, and parttime status [29]. In this case, this result can be thought of as the lower bound in the reduction in transmission risk from the vaccinated household member because exposures may also have occurred from other individuals inside or outside the household.

There are also several proven determinants of SARS-CoV-2 infectiousness that vaccines appear to impact—the magnitude of the peak and rapidity of the decline of the respiratory tract viral load and the severity or number of symptoms (Table 3) [25, 30–34]. Altering these determinants is likely to have an important effect in an infection that has a relatively short and intense period of infectiousness with transmission dynamics characterized by overdispersion [35, 36]. The clinical trial testing the AstraZeneca ChAdOx1 nCoV-19 vaccine in the United Kingdom included weekly SARS-CoV-2 PCR testing, and, among vaccinated participants who became infected, the median minimal cycle threshold value (inversely associated with peak viral load) was 28.8 (interquartile range [IQR], 20.5–33.5), compared with 20.2 (IQR, 15.5–29.6) ( $P < .0001$ ) for infected participants who had received placebo [27]. They also found that vaccinated participants with infection had 1 week shorter

**Table 2. Estimates of Reduced Risk of Transmission in Setting of SARS-CoV-2 Infection After Vaccination**

Vaccine	Study Type/Size	Index Case Details	Effect Size
ChAdOx1 nCoV-19 or BNT162b2 [27]	Transmission study / 552 584 households	Received 1 dose of vaccine at least 21 days before testing positive	Contacts of infected vaccinated household members had 47% reduction (95% CI 0.37–0.47) in infection risk for ChAdOx1 nCoV-19 and 49% reduction (95% CI 0.41–0.56) for BNT162b2
ChAdOx1 nCoV-19 or BNT162b2 [28]	Nationwide cohort study / 338 887	Healthcare workers who were at least 14 days after their second dose of vaccine	Contacts had a 54% (95% CI 50–70%) reduction in infection risk relative to household contacts of unvaccinated HCWs

**Table 3. Effect of Vaccination on Peak Respiratory Tract Viral Load In Breakthrough Cases**

Study Type / Size	Setting	Effect Size
RCT / 8534 (520 infections) [27]	UK	Infected participants who were vaccinated had median minimum cycle threshold of 28.8 (IQR 20.5–33.5) vs. 20.2 (IQR 15.5–29.6) in the unvaccinated group ( $p < 0.0001$ ); duration of PCR positivity 1 week shorter
Observational / 3975 (204 infections) [13]	The United States	Infected participants who were partially or fully vaccinated had a 40% reduction (95% CI 16–57%) in viral load relative to unvaccinated participants, and viral RNA could be detected for 6.2 fewer days (95% CI 4.0–8.4)
Observational / 10 infections [37]	US nursing home	2.4 mean $\log_{10}$ lower viral load at diagnosis after first dose compared with unvaccinated
Observational / 373 402 (12525 infections) [14]	UK	88% reduction in infection with Ct < 30 (95% CI 80–93%, $p < 0.001$ ) relative to Ct $\geq$ 30 after 2 vaccine doses
Observational / 1888 post vaccination infections [38]	Israel	2.8–4.5 fold reduction in viral loads for post vaccination infections 12–37 days after first dose compared with matched unvaccinated controls
Observational / 16 297 positive tests [39]	Israel	Viral loads were 1.6 to 20 fold lower among individuals >60 (75% vaccinated) compared with those age 40–60 (<25% vaccinated)

median duration of PCR positivity. In a study of 3975 healthcare workers, first responders, and frontline workers who received weekly SARS-CoV-2 PCR testing, participants who were partially or fully vaccinated with an mRNA vaccine and became infected had a 40% reduction (95% CI, 16%–57%) in viral load relative to unvaccinated participants, and viral RNA could be detected for 6.2 fewer days (95% CI, 4.0%–8.4%) [13]. Similarly, an observational study of residents of a US Veteran’s Administration nursing home that conducted twice-weekly PCR screening found a 2.4 mean  $\log_{10}$  lower viral load at diagnosis among infected residents who had received the first dose of the Pfizer-BioNTech BNT162b2 vaccine relative to unvaccinated residents with infection [37]. The previously mentioned cohort study of community members in the United Kingdom who regularly underwent SARS-CoV-2 PCR testing found a much greater protection after the second dose of either the AstraZeneca ChAdOx1 nCoV-19 or Pfizer-BioNTech BNT162b2 vaccines against infections with cycle threshold values less than 30 (vaccine effectiveness 88%; 95% CI, 80%–93%) compared with those with cycle threshold values of 30 or greater (vaccine effectiveness 48%; 95% CI, 30%–62%) [14].

Further evidence supporting reduced viral loads during infections after vaccination comes from Israel, which has had the most rapid vaccination

implementation per capita in the world. One observational study compared viral loads between people infected with SARS-CoV-2 who had received the Pfizer-BioNTech BNT162b2 vaccine and demographically matched with unvaccinated people, finding a 2.8- to 4.5-fold reduction in viral loads 12–37 days after the first dose [38]. A complementary study took advantage of a national vaccination program that used age-based eligibility and compared viral loads over time in newly infected individuals 60 years or older (75% of whom were at least 14 days after the first dose of the Pfizer-BioNTech BNT162b2 vaccine at the time of the study) to viral loads in individuals 40 to 60 years old (25% of whom had similar vaccine exposure) [39]. Viral loads at diagnosis, initially similar between the 2 groups, began to separate with vaccine implementation, and the researchers estimated a 1.6- to 20-fold reduction in viral load with vaccination during this early period after the first dose.

In addition to viral load, the severity or number of symptoms is also associated with infectiousness [25, 33]. In addition to multiple real-world vaccine effectiveness studies definitively demonstrating strong protection against severe disease by the mRNA vaccines [1, 2], the interim results for the Janssen AD26.COVID.2.S vaccine presented to the US Food and Drug Administration showed a 24% reduction in symptom severity score on day

1 for infected vaccine recipients relative to those who received placebo, a 47% reduction on day 7, and a 55% reduction on day 14 [40]. Infected participants who had received the Janssen AD26.COVID.2.S vaccine and developed symptoms experienced significantly fewer symptoms compared with those with symptomatic COVID-19 who had received placebo. The previously described cohort study of healthcare workers, first responders, and frontline workers found that participants who were partially or fully vaccinated with an mRNA vaccine and became infected had a 58% lower risk (95% CI, 2%–82%) of having febrile symptoms and had a shorter duration of illness relative to unvaccinated participants, with 2.3 fewer days (95% CI, 0.8%–3.7%) spent sick in bed [13]. Taken together, the available evidence strongly suggests that vaccines decrease the transmission potential of vaccine recipients who become infected with SARS-CoV-2 by at least half.

#### EVIDENCE FROM RANDOMIZED CONTROLLED TRIALS OF MONOCLONAL ANTIBODIES

In addition to data from SARS-CoV-2 vaccines, we can also understand vaccines’ likely effects on transmission through recent evidence from 2 randomized controlled trials of neutralizing monoclonal antibodies used for postexposure prophylaxis [41, 42]. Neutralizing antibodies are one important component of the adaptive immune response induced by vaccines,

and protection provided by therapeutic neutralizing antibodies are also likely to be present with vaccines that elicit a robust polyclonal antibody response. In one study of 300 nursing home residents, administration of the neutralizing monoclonal antibody bamlanivimab resulted in an 77% reduction (95% CI, 52%–89%) in SARS-CoV-2 infection risk relative to placebo during 4 weeks of follow up that included weekly PCR testing [41]. Infected participants who had received bamlanivimab had significantly lower viral loads at diagnosis and more rapid declines in viral load over time. Although this is an important proof of concept, we note that bamlanivimab does not retain neutralizing activity against E484K, one of the key substitutions in variants of concern Beta and Gamma [43].

Similarly, an interim analysis of a study of 409 participants exposed to a household member with COVID-19 had only a small number of events but found a nonstatistically significant 48% reduction (95% CI, 12%–80%) in overall SARS-CoV-2 infection after receiving the combination of casirivimab with imdevimab compared with placebo, with a 100-fold reduction in peak viral load and a significantly shorter duration of positive PCR testing among those who became infected [42].

## CONCLUSIONS

In sum, the data we have reviewed provide compelling evidence that SARS-CoV-2 vaccination results in a substantial reduction in transmission risk, although the exact magnitude of overall transmission reduction is yet to be fully characterized. As a result, the vaccines have much greater potential to decrease population morbidity and mortality than they would in a situation where they only prevented symptomatic disease [44]. These vaccines will thus play a foundational role in curbing and eventually ending the pandemic, as evidenced by the recent dramatic reduction in cases in the United Kingdom and Israel, where vaccination campaigns have successfully

reached a high proportion of the population. Because of this, efforts to achieve rapid and complete global vaccination coverage are even more essential and urgent. Although vaccines remain a scarce resource, the emphasis on vaccinating those with highest risk for adverse outcomes (eg, older individuals) should continue. However, the indirect protection provided by vaccines also suggests strong population benefit from vaccinating people with lower risk for poor clinical outcome who are in larger networks with higher risk of infection—a population for whom preventing transmission is a key outcome [45]. Large reductions in infection risk and decreased viral replication among infected vaccine recipients will also mean less opportunity for the emergence of new variants. Although the great majority of the world remain unvaccinated, nonpharmaceutical interventions will continue to be the fundamental components of strategies to reduce transmission and its consequences.

## Acknowledgments

**Potential conflicts of interest.** All authors: No reported conflicts of interest. All authors have submitted the ICMJE Form for Disclosure of Potential Conflicts of Interest.

## References

- Dagan N, Barda N, Kepten E, et al. BNT162b2 mRNA Covid-19 vaccine in a nationwide mass vaccination setting. *N Engl J Med* **2021**; 384:1412–23.
- Vahidy FS, Pischel L, Tano ME, et al. Real world effectiveness of COVID-19 mRNA vaccines against hospitalizations and deaths in the United States [preprint]. *medRxiv* **2021**.2021.04.21.21255873.
- Mehrotra DV, Janes HE, Fleming TR, et al. Clinical endpoints for evaluating efficacy in COVID-19 vaccine trials. *Ann Intern Med* **2021**; 174:221–8.
- Haug N, Geyrhofer L, Londei A, et al. Ranking the effectiveness of worldwide COVID-19 government interventions. *Nat Hum Behav* **2020**; 4:1303–12.
- Baden LR, El Sahly HM, Essink B, et al; COVE Study Group. Efficacy and safety of the mRNA-1273 SARS-CoV-2 vaccine. *N Engl J Med* **2021**; 384:403–16.
- Sun J, Xiao J, Sun R, et al. Prolonged persistence of SARS-CoV-2 RNA in body fluids. *Emerg Infect Dis* **2020**; 26:1834–8.
- Voysey M, Clemens SAC, Madhi SA, et al; Oxford COVID Vaccine Trial Group. Safety and efficacy of the ChAdOx1 nCoV-19 vaccine (AZD1222) against SARS-CoV-2: an interim analysis of four randomised controlled trials in Brazil, South Africa, and the UK. *Lancet* **2021**; 397:99–111.
- Lipsitch M, Kahn R. Interpreting vaccine efficacy trial results for infection and transmission. *Vaccine* **2021**; 39:4082–8.

- Sadoff J, Gray G, Vandebosch A, et al. Safety and efficacy of single-dose Ad26.COV2.S vaccine against Covid-19. *N Engl J Med* **2021**; 384:2187–201.
- Long QX, Tang XJ, Shi QL, et al. Clinical and immunological assessment of asymptomatic SARS-CoV-2 infections. *Nat Med* **2020**; 26:1200–4.
- Milani GP, Dioni L, Favero C, et al; UNICORN Consortium. Serological follow-up of SARS-CoV-2 asymptomatic subjects. *Sci Rep* **2020**; 10:20048.
- Hall VJ, Foulkes S, Saei A, et al; SIREN Study Group. COVID-19 vaccine coverage in health-care workers in England and effectiveness of BNT162b2 mRNA vaccine against infection (SIREN): a prospective, multicentre, cohort study. *Lancet* **2021**; 397:1725–35.
- Thompson MG, Burgess JL, Naleway AL, et al. Prevention and attenuation of Covid-19 with the BNT162b2 and mRNA-1273 vaccines. *N Engl J Med* **2021**; doi:10.1056/NEJMoa2107058.
- Pritchard E, Matthews P, Stoesser N, et al. Impact of vaccination on SARS-CoV-2 cases in the community: a population-based study using the UK COVID-19 infection survey [preprint]. *Nat Med* **2021**; doi:10.1038/s41591-021-01410-w.
- Tande AJ, Pollock BD, Shah ND, et al. Impact of the COVID-19 vaccine on asymptomatic infection among patients undergoing pre-procedural COVID-19 molecular screening. *Clin Infect Dis* **2021**. doi:10.1093/cid/ciab229.
- Shrotri M, Krutikov M, Palmer T, et al. Vaccine effectiveness of the first dose of ChAdOx1 nCoV-19 and BNT162b2 against SARS-CoV-2 infection in residents of long-term care facilities (VIVALDI study). *Lancet Infect Dis*. **2021**; doi:10.1016/S1473-3099(21)00289-9.
- Weekes M, Jones NK, Rivett L, et al. Single-dose BNT162b2 vaccine protects against asymptomatic SARS-CoV-2 infection. *Elife* **2021**; 10:e68808.
- Thompson MG, Burgess JL, Naleway AL, et al. Interim estimates of vaccine effectiveness of BNT162b2 and mRNA-1273 COVID-19 vaccines in preventing SARS-CoV-2 infection among health care personnel, first responders, and other essential and frontline workers - eight U.S. locations, December 2020–March 2021. *MMWR Morb Mortal Wkly Rep* **2021**; 70:495–500.
- Britton A, Jacobs Slifka KM, Edens C, et al. Effectiveness of the Pfizer-BioNTech COVID-19 vaccine among residents of two skilled nursing facilities experiencing COVID-19 outbreaks - Connecticut, December 2020–February 2021. *MMWR Morb Mortal Wkly Rep* **2021**; 70:396–401.
- Cavanaugh AM, Fortier S, Lewis P, et al. COVID-19 outbreak associated with a SARS-CoV-2 R.1 lineage variant in a skilled nursing facility after vaccination program - Kentucky, March 2021. *MMWR Morb Mortal Wkly Rep* **2021**; 70:639–43.
- Barda N, Dagan N, Balicer RD. BNT162b2 mRNA Covid-19 vaccine in a nationwide mass vaccination setting. *Reply. N Engl J Med* **2021**; 384:1970.
- Dejnirattisai W, Zhou D, Supasa P, et al. Antibody evasion by the P.1 strain of SARS-CoV-2. *Cell* **2021**; 184:2939–54.e9.
- Edara VV, Norwood C, Floyd K, et al. Infection- and vaccine-induced antibody binding and neutralization of the B.1.351 SARS-CoV-2 variant. *Cell Host Microbe* **2021**; 29:516–21.e3.
- Liu Y, Liu J, Xia H, et al. Neutralizing activity of BNT162b2-elicited serum. *N Engl J Med* **2021**; 384:1466–8.
- Qiu X, Nergiz AI, Maraolo AE, et al. The role of asymptomatic and pre-symptomatic infection in SARS-CoV-2 transmission - a living systematic review. *Clin Microbiol Infect* **2021**; 27:511–9.

26. Cevik M, Tate M, Lloyd O, et al. SARS-CoV-2, SARS-CoV, and MERS-CoV viral load dynamics, duration of viral shedding, and infectiousness: a systematic review and meta-analysis. *Lancet Microbe* **2021**; 2:e13–22.
27. Emary KRW, Golubchik T, Aley PK, et al; COVID-19 Genomics UK consortium; AMPHEUS Project; Oxford COVID-19 Vaccine Trial Group. Efficacy of ChAdOx1 nCoV-19 (AZD1222) vaccine against SARS-CoV-2 variant of concern 202012/01 (B.1.1.7): an exploratory analysis of a randomised controlled trial. *Lancet* **2021**; 397:1351–62.
28. Harris RJ, Hall JA, Zaidi A, et al. Effect of vaccination on household transmission of SARS-CoV-2 in England. *N Engl J Med* **2021**. doi:10.1056/NEJMc2107717.
29. Shah ASV, Gribben C, Bishop J, et al. Effect of vaccination on transmission of COVID-19: an observational study in healthcare workers and their households [preprint]. *medRxiv* **2021**:2021.03.11.21253275.
30. Marks M, Millat-Martinez P, Ouchi D, et al. Transmission of COVID-19 in 282 clusters in Catalonia, Spain: a cohort study. *Lancet Infect Dis* **2021**; 21:629–36.
31. Lyngse FP, Mølbak K, Trøholt Frank K, et al. Association between SARS-CoV-2 transmission risk, viral load, and age: a nationwide study in Danish households [preprint]. *medRxiv* **2021**:2021.02.28.21252608.
32. Bjorkman KK, Saldi TK, Lasda E, et al. Higher viral load drives infrequent SARS-CoV-2 transmission between asymptomatic residence hall roommates [preprint]. *medRxiv* **2021**:2021.03.09.21253147.
33. Sayamanathan AA, Heng CS, Pin PH, et al. Infectivity of asymptomatic versus symptomatic COVID-19. *Lancet* **2021**; 397:93–4.
34. Lee LYW, Rozmanowski S, Pang M, et al. An observational study of SARS-CoV-2 infectivity by viral load and demographic factors and the utility lateral flow devices to prevent transmission. *medRxiv*. doi:10.1101/2021.03.31.21254687.
35. Meyerowitz EA, Richterman A, Gandhi RT, Sax PE. Transmission of SARS-CoV-2: a review of viral, host, and environmental factors. *Ann Intern Med* **2021**; 174:69–79.
36. Goyal A, Reeves DB, Cardozo-Ojeda EF, et al. Viral load and contact heterogeneity predict SARS-CoV-2 transmission and super-spreading events. *eLife* **2021**; 10:e63537.
37. McEllistrem MC, Clancy CJ, Buehrle DJ, et al. Single dose of a mRNA SARS-CoV-2 vaccine is associated with lower nasopharyngeal viral load among nursing home residents with asymptomatic COVID-19. *Clin Infect Dis* **2021**. doi:10.1093/cid/ciab263.
38. Levine-Tiefenbrun M, Yelin I, Katz R, et al. Initial report of decreased SARS-CoV-2 viral load after inoculation with the BNT162b2 vaccine. *Nat Med* **2021**; 27:790–2.
39. Petter E, Mor O, Zuckerman N, et al. Initial real world evidence for lower viral load of individuals who have been vaccinated by BNT162b2 [preprint]. *medRxiv* **2021**:2021.02.08.21251329.
40. Sponsor Briefing Document - Janssen AD26. COV2.S Vaccine for the Prevention of COVID-19. Vaccines and Related Biological Products Advisory Committee Meeting February 26, 2021. Available at: <https://www.fda.gov/media/146219/download>. Accessed 6 March 2021.
41. Cohen MS, Nirula A, Mulligan M, et al. Bamlanivimab prevents COVID-19 morbidity and mortality in nursing-home setting. Conference on Retroviruses and Opportunistic Infections 2021. Virtual. Abstract 121; **2021**.
42. O'Brien M, Forleo Neto E, Chen K, et al. Casirivimab with imdevimab antibody cocktail for COVID-19 prevention: interim results. Conference on Retrovirology and Opportunistic Infections 2021. Virtual. Abstract 123; **2021**.
43. Widera M, Wilhelm A, Hoehl S, et al. Bamlanivimab does not neutralize two SARS-CoV-2 variants carrying E484K in vitro. *medRxiv* **2021**:2021.02.24.21252372.
44. Swan DA, Bracis C, Janes H, et al. COVID-19 vaccines that reduce symptoms but do not block infection need higher coverage and faster rollout to achieve population impact [preprint]. *medRxiv* **2020**:2020.12.13.20248142.
45. Goldenbogen B, Adler SO, Bodeit O, et al. Optimality in COVID-19 vaccination strategies determined by heterogeneity in human-human interaction networks [preprint]. *medRxiv* **2020**:2020.12.16.20248301.