Vaccine 40 (2022) 3165–3173

Contents lists available at ScienceDirect

Vaccine

journal homepage: www.elsevier.com/locate/vaccine

De-escalation of asymptomatic testing and potential of future COVID-19 outbreaks in US nursing homes amidst rising community vaccination coverage: A modeling study

Brajendra K. Singh *, Joseph Walker, Prabasaj Paul, Sujan Reddy, Camden D. Gowler, John Jernigan, Rachel B. Slayton

CDC COVID-19 Response Team, Centers for Disease Control and Prevention, Atlanta, GA 30329, USA

ARTICLE INFO

Article history:
Received 16 December 2021
Received in revised form 6 April 2022
Accepted 11 April 2022
Available online 18 April 2022

Keywords:
COVID-19
SARS-CoV-2
Nursing home
Healthcare personnel
Mathematical modeling
Outbreak
mRNA vaccines

ABSTRACT

As of 2 September 2021, United States nursing homes have reported >675,000 COVID-19 cases and >134,000 deaths according to the Centers for Medicare & Medicaid Services (CMS). More than 205,000,000 persons in the United States had received at least one dose of a COVID-19 vaccine (62% of total population) as of 2 September 2021. We investigate the role of vaccination in controlling future COVID-19 outbreaks.

We developed a stochastic, compartmental model of SARS-CoV-2 transmission in a 100-bed nursing home with a staff of 99 healthcare personnel (HCP) in a community of 20,000 people. We parameterized admission and discharge of residents in the model with CMS data, for a within-facility basic reproduction number (R_0) of 3.5 and a community R_0 of 2.5. The model also included: importation of COVID-19 from the community, isolation of SARS-CoV-2 positive residents, facility-wide adherence to personal protective equipment (PPE) use by HCP, and testing. We systematically varied coverage of mRNA vaccine among residents, HCP, and the community. Simulations were run for 6 months after the second dose in the facility, with results summarized over 1,000 simulations.

Expected resident cases decreased as community vaccination increased, with large reductions at high HCP coverage. The probability of a COVID-19 outbreak was lower as well: at HCP vaccination coverage of 60%, probability of an outbreak was below 20% for community coverage of 50% or above. At high coverage, stopping asymptomatic screening and facility-wide testing yielded similar results.

Results suggest that high coverage among HCP and in the community can prevent infections in residents. When vaccination is high in nursing homes, but not in their surrounding communities, asymptomatic and facility-wide testing remains necessary to prevent the spread of COVID-19. High adherence to PPE may increase the likelihood of containing future COVID-19 outbreaks if they occur.

Published by Elsevier Ltd.

1. Background

The coronavirus disease-19 (COVID-19) pandemic has disproportionately impacted nursing homes (or care homes) globally [1], including in the United States. According to the US Centers for Medicare and Medicaid Services (CMS), as of 2 September 2021, there have been >675,000 reported confirmed COVID-19 cases and >134,000 deaths of nursing home residents in the United States [2], representing 2% of total reported cases and 21% of total COVID-19 deaths in the United States, respectively [3]. Regular screening of asymptomatic staff, along with facility-wide testing upon detection of a COVID-19 case, and high adherence to other infection prevention and control (IPC) practices have been the main policies in the management and control of COVID-19 outbreaks in nursing homes.

More than 205,000,000 persons in the United States had received, at least, one dose of a COVID-19 vaccine (62% of total

Abbreviations: CMS, Centers for Medicare and Medicaid Services; HCP, Healthcare personnel; IPC, Infection prevention and control; PPE, Personal protective equipment; NH, Nursing home; COVID-19, Coronavirus disease-2019; SARS-CoV-2, Severe acute respiratory syndrome coronavirus-2; VC, Vaccination coverage.

* Corresponding author at: Centers for Disease Control and Prevention, 1600 Clifton Rd, MS H16-3, Atlanta, GA 30333, USA.

E-mail addresses: nka8@cdc.gov (B.K. Singh), jo.walker@yale.edu (J. Walker), vig5@cdc.gov (P. Paul), kuj0@cdc.gov (S. Reddy), nrt8@cdc.gov (C.D. Gowler), jqj9@cdc.gov (J. Jernigan), via3@cdc.gov (R.B. Slayton).

https://doi.org/10.1016/j.vaccine.2022.04.040
0264-410X/Published by Elsevier Ltd.

population) and 82% of adults aged ≥65 years had received ≥1 doses of a COVID-19 vaccine as of 2 September 2021 [3]. Vaccination generated a significant reduction in the incidence rate of confirmed COVID-19 cases in the age-cohort of adults aged ≥65 years [4,5]. In the United States, statewide percentages of nursing home residents who are fully vaccinated ranged from 65% to 97% and 40% to 78% for healthcare personnel (HCP) [6].

Nursing homes are congregate settings [7,8] where residents, often with multiple comorbidities, share HCP for general and medical care. Therefore COVID-19 incidence in these congregate settings may be correlated with COVID-19 incidence in surrounding communities [7]. As a result, nursing homes may not be able to prevent future COVID-19 outbreaks if vaccine coverage among HCP and the surrounding community is low.

In the pre-vaccine phase of the COVID-19 pandemic, IPC practices were implemented to detect and control COVID-19 outbreaks [9,10]. The IPC practices included use of recommended personal protective equipment (PPE), visitor restrictions, and isolation (or work restriction in the case of HCP) of persons who tested positive for COVID-19. Testing practices included testing if symptomatic, as part of routine (e.g., weekly) asymptomatic staff screening, or in response to an outbreak (i.e., testing all residents and HCP twice every week). Previous studies have affirmed the important role of IPC practices, including regular testing of residents and staff, in the early detection and control of COVID-19 outbreaks in nursing homes [11–13]. In an early vaccine modeling study, regular testing of nursing home residents and staff, as well as adhering to IPC policies, were key in managing COVID-19 in nursing home settings, especially when vaccination coverage in the surrounding community was low [14]. When community vaccine coverage is high, the overall incidence of SARS-CoV-2 is low, thereby decreasing the risk of introducing SARS-CoV-2 (the virus that causes COVID-19) into nursing homes.

When vaccination coverage among nursing home staff members and the surrounding community is low, preventing the introduction and spread of SARS-CoV-2 in nursing homes relies entirely on consistent adherence to IPC practices. Adherence to IPC practices in nursing homes can vary and may not adequately control transmission for several reasons. For example, adherence to IPC practices may likely be low when routine testing of residents and HCP poses an unmanageable burden (e.g., shortages of testing supplies or trained personnel), when overall PPE implementation is not planned adequately [15,16], or when a facility faces staff shortages [17,18].

We investigated the role of vaccination coverage in the management of future COVID-19 outbreaks in nursing homes. In this modeling exercise, we also tested our hypothesis that routine testing in nursing homes could be de-escalated or lifted safely, in the presence of high vaccination coverage among residents and HCP and in the surrounding community. Finally, we explored the potential benefits of maintaining adequate adherence to recommended use of PPE by nursing home staff for reducing or preventing the risk of SARS-CoV-2 introduction and future COVID-19 outbreaks in nursing homes.

2. Materials and methods

2.1. Model overview

We developed a stochastic, compartmental Susceptible-Exposed-Infectious (asymptomatic/symptomatic)-Recovered (SEIR) model of SARS-CoV-2 transmission in a theoretical 100-bed single-occupancy nursing home (NH) with a total staffing pool of 99 healthcare personnel (HCP) in a community of 20,000 people (see **Characteristics of an average nursing home in the United States** in Supplementary Material Appendix 1). In brief, there are eight compartments in our NH model. These are S (susceptible), E (exposed), P (presymptomatic), I (symptomatic), A (asymptomatic), H (isolated), R (recovered) and D (dead). We made several simplifying assumptions. We assumed that there was no difference in infectivity of asymptomatic and presymptomatic/symptomatic individuals. People in the R compartment were assumed to be immune for the rest of simulation time period. The compartment D tracks only the COVID-19 induced deaths. Because people in the HCP subpopulation spent most of their time in the community, we did not consider a D compartment for this subpopulation. This may also be reasonable due to our assumption about temporary replacement of SARS-CoV-2 positive staff member due to work restriction. In the model, we considered two routes of transmission: within-subpopulation (e.g., residents-to-residents) and between-subpopulation (e.g., residents-to-HCP) transmission routes. Simple model flow diagrams of resident, HCP, and community compartments are shown in Fig. 1. (A detailed version of flow-diagram depicting transmission pathways between NH residents and HCP, and isolation of residents when tested positive for SARS-CoV-2 is provided in Figure S1 in Supplementary Material Appendix 1).

We assumed that HCP work-shifts were 8 h long, requiring 33 members of HCP to be present in the facility at any time of day. An 8-hour work-shift implies that HCP spend two-thirds of a day in the community, which results in movement of HCP between the community and the facility in which they work (bottom double arrow in Fig. 1). In this compartmental model, we do not model the HCP flow *per se* between the facility and the community due to shift change. Rather we model the effect of movement of HCP between community and facility on SARS-CoV-2 transmission between community dwellers and HCP by a modified daily contact rate. The modified contact rate was parametrized by multiplying the daily community contact rate by 2/3 to account for HCP staying one-third (i.e., 8 h) of a day in the facility. We also assumed that contact patterns between residents and staff members did not differ between day and night shifts. The baseline model is parameterized to have a within-facility basic reproduction number (R_0) of 3.5 [11] and a community R_0 of 2.5 [19,20], where R_0 presents the average number of new cases generated by an infected person [21]. Model parameters with detailed descriptions are provided in Table S1 (Supplementary Material Appendix 1).

The model incorporates the following processes of movements of individuals between the nursing home and the community: admission and discharge of residents (which was parameterized with the US Centers for Medicare & Medicaid Services (CMS) data from January to September 2020 [22], see Supplementary Material Appendix 1 Figure S1A) with an assumption of full occupancy (i.e., discharges/deaths were balanced by admissions) in the nursing home during the entire simulation period; daily visits from community members to residents, which is indirectly modeled in terms of risk of susceptible visitors being exposed to SARS-CoV-2 by coming into contact with infectious residents or *vice versa*; work restriction of HCP upon testing positive for SARS-CoV-2, in which the HCP with infection was replaced by a non-symptomatic community person (i.e., persons from the susceptible, exposed, presymptomatic/asymptomatic and recovered community compartments). The model also incorporates symptom-based screening/testing of residents and staff plus routine weekly testing of asymptomatic HCP. This testing may trigger the isolation of positive residents within the facility, and work restriction and temporary replacement of positive HCP, as mentioned above. A regular (twice-weekly) facility-wide testing of residents and staff, regardless of their vaccination status, was also implemented once a COVID-19 case was identified in the facility. All testing was implemented via a point-of-care (POC) test such as a rapid antigen test.

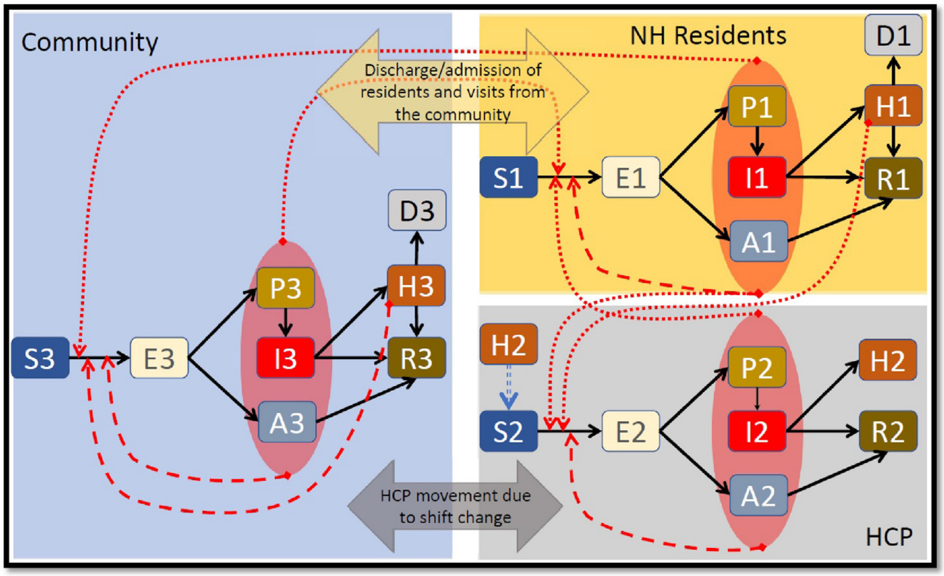

Fig. 1. Flow diagrams of SARS-CoV-2 transmission in residents, healthcare personnel (HCP) and people in the community. Numbers denote disease compartments for: 1 = resident, 2 = HCP, and 3 = community populations. The capital letters inside the boxes indicate disease statuses as follows: S = susceptible; E = exposed; P = presymptomatic; I = infected/symptomatic; A = asymptomatic; H = hospitalized/isolated; R = recovered; and D = dead. The **solid** black arrows depict the outflow from one compartment to the next. The red **dashed** arrows represent within-population transmission routes between susceptible and infectious individuals. The red **dotted** arrows depict transmission between susceptible and infectious individuals between pairs of any two populations (of residents, HCP, or community dwellers). Note that there is a red dotted arrow for depicting a transmission route between isolated residents and susceptible HCP. The double-dashed arrow, emanating from the free-standing H2-compartment, depicts temporary replacement of HCP in which staff members lost due to work-restriction for home-isolation is compensated for by an equivalent number of susceptible HCP. Here the depiction of temporary replacement is shown to happen into susceptible HCP compartment only, which is done for clarity. A proportional replacement is modeled to happen into five HCP compartments. See for details the set of ordinary differential equations in Supplementary Material Appendix 1. Admission of residents from the community into the facility and their discharges from the facility are shown by top left–right arrow, which is also used to depict flow of the community visitors. Discharges include deaths and the use of left–right arrow means that a discharge is balanced by an admission. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Although the sensitivity of POC tests can vary widely depending on specimen characteristics [23,24], here we assumed test sensitivity of 80% (for symptomatic persons) and 60% (for asymptomatic persons), which are in the range reported in one study [23] We also assumed 100% specificity and test-result turnaround time of 15 min. In addition, we also modeled facility-level adherence to PPE practices by HCP. A simple model of the effect of PPE adherence on transmission was applied by multiplying the transmission coefficient with (1-PPE adherence), where "PPE adherence" was proportional to the fraction of time PPE was used correctly with an assumed PPE efficacy of 100%.

2.2. Testing strategies

In order to test our hypothesis about the de-escalation of routine testing, we ran these modeling experiments for two testing strategies: (1) a default strategy which included symptom-based screening of residents and HCP, along with weekly testing of all asymptomatic staff members plus facility-wide twice-weekly testing if a COVID-19 case was identified; and (2) an alternate strategy which included only symptom-based screening of residents and HCP, without regular asymptomatic testing of staff or facility-wide testing.

2.3. Vaccination

We assumed the following about vaccination: nursing home residents and HCP were vaccinated with dose 1 of an mRNA vaccine at the start of day 1; the second dose of the vaccine was administered after 28 days; either 65% (low), 75% (intermediate), or 85% (high) of nursing home residents were assumed to be vaccinated, while either 40% (low), 60% (intermediate), or 80% (high) of HCP were assumed to be vaccinated. We ran the model with 25% to 75% (in 5% increments) of the community being fully vaccinated on day 1. In addition, we assumed that vaccination coverage among HCP and other community members could differ. This assumption ensures that the effect of vaccination coverage on transmission within the facility is discernable regardless of community vaccination coverage.

2.4. ***Vaccine*** *effectiveness* ***(VE)***

We assumed values (Table 1), based on current knowledge (as of 15 May 2021) about effectiveness of mRNA vaccines [25–29]. We assumed that VE against severe disease and VE against infectiousness do not differ between nursing home residents, HCP, and community members. Although no direct estimates existed for VE against infectiousness at the time this analysis was conducted (a few studies have since been published, see [30–33]), evidence suggests that persons with breakthrough infection may have substantially lower viral loads than unvaccinated persons with infections [34]. Because viral load is a key driver in SARS-CoV-2 transmission [35], we made this simplifying assumption about reduced infectiousness for persons with infection after vaccination. We also conducted sensitivity analyses for reduced VE against infection values, without or with the reduced values of VE against severe disease and VE against onward transmission as described below.

2.5. Modeling the effect of mRNA vaccine on SARS-CoV-2 transmission

We have provided a flow diagram in Supplementary Appendix 1 Figure S1B, which illustrates the flow from one disease compartment to the next in the population of vaccinated persons. We stud-

Table 1
Assumed vaccine effectiveness (VE) values.

	VE against infection		VE against severe disease		VE against onward transmission	
	Partial protection	Full protection	Partial protection	Full protection	Partial protection	Full protection
Residents	75%	90%	64%	94%	50%	90%
HCP	80%	90%	64%	94%	50%	90%
Community members	80%	90%	64%	94%	50%	90%

Partial protection is assumed to reach 14 days after receiving the 1st dose.
Full protection is assumed to reach 14 days after receiving the 2nd dose.

ied the effect of mRNA vaccines on the SARS-Cov-2 transmission as a leaky vaccine. We multiplied the transmission rate with $(1 - \text{VE against infection})$ for evaluating the protection of vaccinated persons from getting infected with the virus. In the case of breakthrough infections, proportion of people developing symptoms was reduced from $(1 - a)$ to $(1 - a) \times (1 - \text{VE against severe disease})$. Here the parameter a represents the proportion of asymptomatic infection (Table S1 in Supplementary Material Appendix 1). The COVID-19-induced death rate among symptomatic breakthrough cases was reduced by a factor $(1 - \text{VE against severe disease})$. Similarly, infectiousness of breakthrough cases was reduced to $(1 - \text{VE against onward transmission})$.

2.6. Facility-level PPE adherence

Adherence to PPE use by healthcare staff in nursing homes has been less than optimal before the COVID-19 pandemic [36]. In the beginning of the pandemic, initial CMS surveys (during the week of March 30, 2020) found that 25% of inspected facilities failed to demonstrate proper use of PPE [37]. During early phase of the pandemic, US nursing homes faced severe PPE shortages [38,39], which may have impacted PPE use adherence by nursing home staff [39]. In this modeling analysis, therefore, simulations were performed for three levels of PPE adherence (in terms of percentage of time HCPs properly use recommended PPE during interactions with residents): 25% (poor adherence), 50% (intermediate adherence) and 75% (high adherence).

2.7. Initial conditions

Infection in the model was initialized in the community compartments with an incidence rate of 200 cases per 100,000 people, which results in 40 persons with infection for a community population of 20,000 people. In simulations, the initial seeding of infection in the nursing home via importation of infections from the community was allowed 14 days after the administration of the first dose of mRNA vaccines. This assumption was made to improve comparisons across scenarios evaluated.

2.8. Sensitivity analysis of VE values

In order to capture the effect of reduced VEs [40,41] and/or increased transmissibility on SARS-CoV-2 in the facility, for example, as might occur with new variants we performed the following sensitivity analyses:

1. Reduced VE against infection. The other model parameters were kept unchanged. The values of VE against infection were reduced to three-fourth of the original values (i.e., reduced VE against infection: 56.3% (partial) and 67.5% (full) for residents, and 60% (partial) and 67.5% (full) for HCP/community members).
2. Reduced VE against severe disease and VE against onward transmission. The other model parameters were kept unchanged. The values of VE against severe disease and VE against onward transmission were halved (i.e., reduced VE against severe disease: 32% (partial) and 47% (full) and reduced VE against onward transmission: 25% (partial) and 45% (full) for all three subpopulations: residents, HCP and community people).
3. Reduced VE against infection as in (1) + Reduced VE against severe disease and VE against onward transmission as in (2). The other model parameters were kept unchanged.
4. Reduced VE against infection as in (1) + increased transmissibility in the facility and general community. Increased transmissibility was assumed to be 1.5 × the original level (which increased the within-facility and community basic reproduction numbers, respectively, to 5.3 and 3.8).
5. Reduced VE against infection as in (1) + transmissibility in the facility and in the general community was increased by a factor of 2 (which increased the within-facility and community basic reproduction numbers, respectively, to 7 and 5).

2.9. Sensitivity analysis of equal infectiousness of asymptomatics versus symptomatics

In our nursing home model, we made a parsimonious assumption that symptomatic and asymptomatic residents were equally infectious. We had made this assumption due to a lack of clear evidence against it in the population of nursing home residents. Although debate around this issue is ongoing [42], we performed limited sensitivity analysis by assuming asymptomatically infected persons to be 70% infectious compared to symptomatic persons.

2.10. Measured outcomes

The main outcome was the total number of symptomatic cases among nursing home residents at the end of model simulations. The secondary outcome was probability of avoiding a nursing home outbreak during the 4-week period after residents and HCP were fully vaccinated. Two types of nursing home outbreaks were considered: (i) any outbreak (≥1 symptomatic cases in residents or HCP) and (ii) a large outbreak (defined as ≥5 symptomatic cases in residents or HCP). The probability of avoiding an outbreak was calculated as 1 minus the fraction of simulations in which the outbreak threshold was met over the evaluation period.

2.11. Simulations and analysis of model outputs

All simulations were run for a period of 6 months after 14 days of the second dose in the nursing home. The main outcome was summarized as the mean (or median) plus 90% confidence interval (estimated as 5th and 95th percentile values) across 1,000 stochastic simulations for any combination of vaccination coverages considered among nursing home residents and HCP, and in the community. There were 99 unique combinations of vaccination coverage levels (3, 3, and 11 possible levels for residents, HCP, and community members, respectively). Each vaccination coverage combination was simulated at 3 facility-level PPE adherence values.

2.12. *Availability of computer code*

Computer code for the nursing home SARS-CoV-2 transmission model was developed in MATLAB (R2020b) and optimized to run in a parallel computing environment. The computer code of the model is provided as text in Supplementary Material Appendix 3 as well as at https://www.zenodo.org. The DOI is https://doi.org/10.5281/zenodo.6306305.

3. Results

For any given HCP vaccination coverage, the expected number of symptomatic cases in nursing home residents decreased as vaccination coverage in the community rose from 25% to 75% (Fig. 2), with a notable decline once community coverage exceeded 50%. Meanwhile, when community vaccination coverage was fixed, increasing HCP vaccination coverage from 40% to 80% led to a decrease in the expected number of symptomatic nursing home cases. Left and right panels in Fig. 2, respectively, show these results from model simulations with and without asymptomatic testing strategy in place, with 65% (top row), 75% (middle row), and 85% (bottom row) resident vaccination coverages and low (25%) PPE adherence facility-wide. The impact of increasing HCP vaccination coverage was most pronounced when community vaccination coverage was low, indicating the importance of high vaccination coverage among staff members in controlling SARS-CoV-2 transmission in nursing homes when community transmission is ongoing. When vaccination coverages in the community and among residents were 25% and 65%, respectively, increasing HCP vaccination coverage from 40% to 80% was associated with up to a 45% reduction in expected resident cases. On the other hand, if community vaccination coverage was sufficiently high (≥65%), the mean number of symptomatic resident cases was very low (≤5 over a 6-month period), even at the lowest resident and HCP vaccination coverage levels that we explored (65% and 40%, respectively). As resident vaccination coverage increased from 65% to 85%, variability in the number of symptomatic resident cases between simulations (as measured by the width of the 90% confidence interval) reduced significantly (up to 30%). Increasing community vaccination coverage from 25% to 75% was associated with even greater reductions (>90%) in mean resident cases, regardless of resident and/or HCP vaccination coverages. Increasing facility-level PPE adherence from 25% to 50% (Supplementary Material Appendix 2 Figure S2A) to 75% (Supplementary Material Appendix 2 Figure S2B) notably reduced resident cases (compare Fig. 2 to Supplementary Material Appendix 2 Figures S2A & S2B).

When community vaccination coverage was ≥60%, resident cases were similar in model simulations with and without asymptomatic testing (Fig. 2). Mean and median cumulative resident cases may differ for alternate and default testing strategies depending on PPE adherence and vaccination coverage (Table 2). Asymptomatic testing had the greatest impact for facility-level PPE adherence of 25% and lowest vaccination coverages, respectively, among community members (40%), staff (40%), and residents (65%). Differences in both mean and median cases were 5 between the default and alternative testing strategies. However, increasing community vaccination coverage from 40% to 60% reduced the impact of asymptomatic testing. A difference in the means of cumulative symptomatic resident cases under alternate testing strategy versus default testing strategy was 4.9, which reduced to 1.5 when community vaccination coverage rose from 40% to 60% (Table 2). The importance of testing decreased as adher-

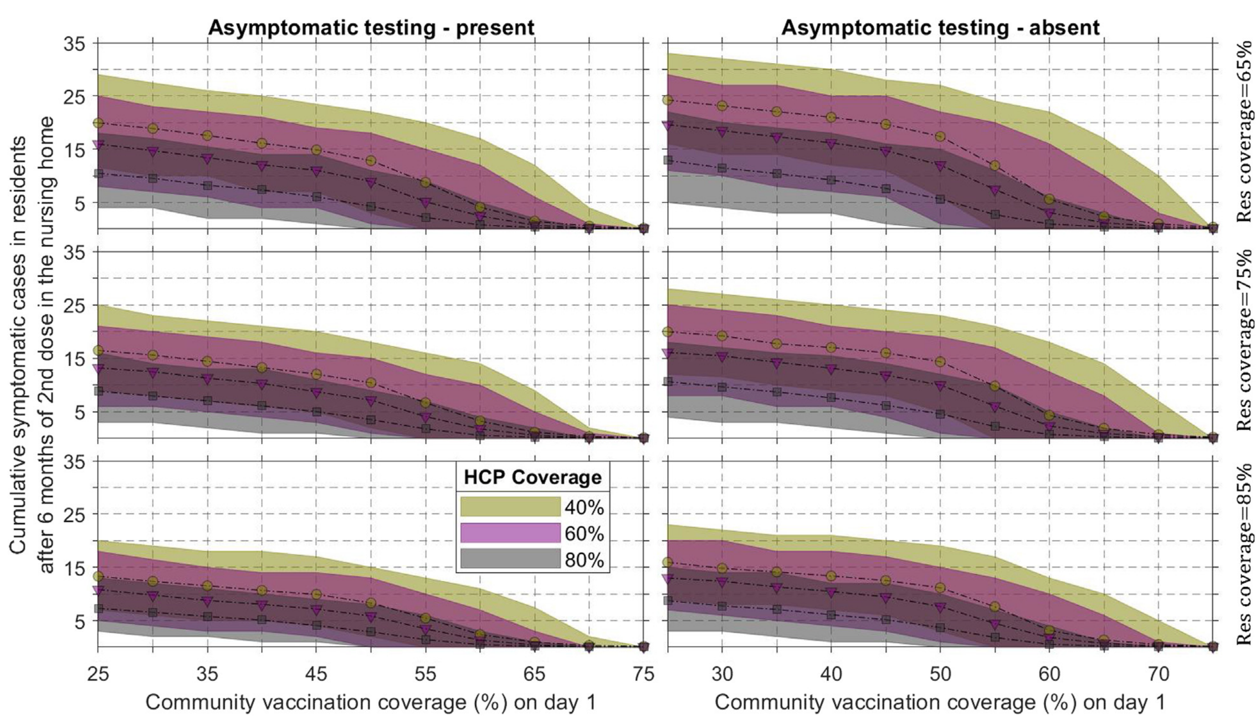

Fig. 2. Decrease in resident cases in nursing home (NH) with rise in vaccination coverage in the community. In each panel, we plotted the mean number (shown by a point marker) of cumulative symptomatic cases in residents 6 months after 2nd dose and their 90% confidence interval (shown by the width of a color band) for three healthcare personnel (HCP) vaccination coverages: 40%, 60%, or 80%. The top row is for NH resident vaccination coverage of 65%, the middle for 75%, and the bottom row for vaccination coverage of 85%. The left panel results are from model simulations with default testing strategy (symptomatic screening plus facility-wide regular testing (weekly testing of asymptomatic HCP and twice-weekly facility-wide testing once a COVID-19 case was identified) whereas the right panel results are from model simulations with only symptomatic screening. In both panels, facility-level adherence to using recommended personal protective equipment was 25%.

Table 2
Difference in the mean and median of cumulative counts of symptomatic resident cases from model simulations under alternate versus default testing strategies.

	PPE adherence = 25%		PPE adherence = 50%		PPE adherence = 75%	
Community vaccination coverage (%)	**Difference in the means**	**Difference in the medians**	**Difference in the means**	**Difference in the medians**	**Difference in the means**	**Difference in the medians**
Low vaccination coverage in nursing home (resident VC = 65% and staff VC = 40%)						
40	4.9	5	3.9	4	2.3	3
50	4.6	5	3.5	4	2.2	3
60	1.5	0	1.0	0	0.6	0
Medium vaccination coverage in nursing home (resident VC = 75% and staff VC = 60%)						
40	2.8	3	2.3	2	1.3	1
50	2.8	3	1.9	2	1.3	1
60	0.6	0	0.3	0	0.2	0
High vaccination coverage in nursing home (resident VC = 85% and staff VC = 80%)						
40	1.0	1	0.8	1	0.7	0
50	0.8	1	0.5	1	0.4	0
60	0.1	0	0.0	0	0.1	0

VC = vaccination coverage; difference in the means = (the mean number of symptomatic cases in residents under alternate testing strategy) - (the mean number of symptomatic cases in residents under default testing strategy); difference in the medians = (the median number of symptomatic cases in residents under alternate testing strategy) - (the median number of symptomatic cases in residents under default testing strategy); default testing strategy included symptom-based screening of residents and HCP, along with weekly testing of all asymptomatic staff members plus facility-wide twice-weekly testing once a COVID-19 case is identified; and alternate testing strategy included only symptom-based screening of residents and HCP, but no weekly testing of all asymptomatic staff nor facility-wide twice-weekly testing upon a case detection.

ence to PPE usage and vaccination coverage increased. When vaccination coverage was high in the community (60%), in staff (80%), and among residents (85%), asymptomatic testing had practically no marginal effect on cases (0.1 and 0 difference in mean/median cases between testing strategies), regardless of PPE adherence. We have compared differences in the mean and the median of resident cases between two testing strategies for the considered combinations of vaccination coverages among residents, staff and community persons (Table S2). When we compared the distributions of cumulative resident cases under the default and alternate testing strategies, they started to become identical at higher PPE adherence and staff/resident or community vaccination coverage (Supplementary Material Appendix 2 Figure S2H).

As community vaccination coverage and HCP coverage increased, the probability of avoiding an outbreak increased (Fig. 3). When community vaccination coverage was ≥55%, there was no major difference in the probability of avoiding any outbreak or a large outbreak across the three HCP vaccination coverage scenarios we modeled. Maximizing HCP vaccination coverage becomes more important for preventing outbreaks at low levels of community vaccination coverage.

Sensitivity analyses showed that reduced VE against infection alone did not have a large impact on the cumulative number of symptomatic resident cases, with mean cases increasing by no>2 from the original estimates (Supplementary Material Appendix 2 Figures S2C1 – S2C3). However, variability in cases between simulations did increase as VE was reduced, even when community vaccination coverage was high (≥60%). Variability in cases between simulations increased further when VE against severe disease and VE against infectiousness were halved but VE against infection was kept at the original values (Supplementary Material Appendix 2 Figures S2D1 – S2D3). Simulations with reduction in all three VEs produced significantly more resident cases (Supplementary Material Appendix 2 Figures S2E1 – S2E3), compared to the simulations done with the original VEs.

Simulations with reduced VE and increased transmissibility (e.g., as could be seen with specific variants of SARS-CoV-2) generated significantly more resident cases, relative to the original scenario. For the default testing strategy and low community vaccination coverage (25%), reduced VE against infection and a 1.5x or 2x increase in transmissibility was associated with ≥50% and ≥76% increases in expected resident cases, compared to our primary estimates. These results are presented in Supplementary Material Appendix 2 Figures S2F1 – S2F3 and Supplementary Material Appendix 2 Figures S2G1 – S2G3 for 1.5x and 2x increases in transmissibility, respectively. Even under the highest community vaccination coverage (75%) considered, the expected number of resident cases never went below 1. However, maintaining facility-wide PPE adherence of 75% and at least 75% vaccination coverage in residents, staff, and community members was able to keep expected resident cases ≤5 (Supplementary Material Appendix 2 Figure S2D3) and ≤10 (Supplementary Material Appendix 2 Figure S2E3) under the 1.5x and 2x increased transmissibility scenarios, respectively.

Results from a limited sensitivity analysis on equal infectiousness of asymptomatics versus symptomatics are shown in Supplementary Appendix 2 Figure S2I. Uncertainty in resident cases was less when asymptomatically infected persons were assumed 70% infectious compared to symptomatic persons than when both were assumed equally infectious under our parsimonious assumption.

4. Discussion

Our results suggest that increasing community vaccination coverage leads to fewer cases among nursing home residents. These results suggest that at low to medium community vaccination coverages increasing HCP vaccination coverage reduces resident cases. This finding agrees with the results reported by McGarry et al. [43] that nursing homes with low staff vaccination coverage had higher numbers of cases than those with high staff vaccination coverage. Reductions in cases were most significant when community vaccination coverage was increased from a low level (<50%). Reported vaccination coverages on average have ranged from 49.2% for certified nursing assistants to 61.0% for registered nurses and licensed practical nurses among nursing home staff [44]. Promoting high vaccination coverage among HCP may be key to preventing large outbreaks in these congregate facilities when vaccination coverage in the surrounding community is low. For example, at community vaccination coverage of 35%, an increase in HCP vaccination coverage from 40% to 80% led to the probability of preventing a large outbreak from 65% to 87% (Fig. 3). This finding strengthens the call for increasing vaccination coverages among US nursing home staff members [14], which is consistent with the findings of previous randomized control trials investigating the role of increased uptake

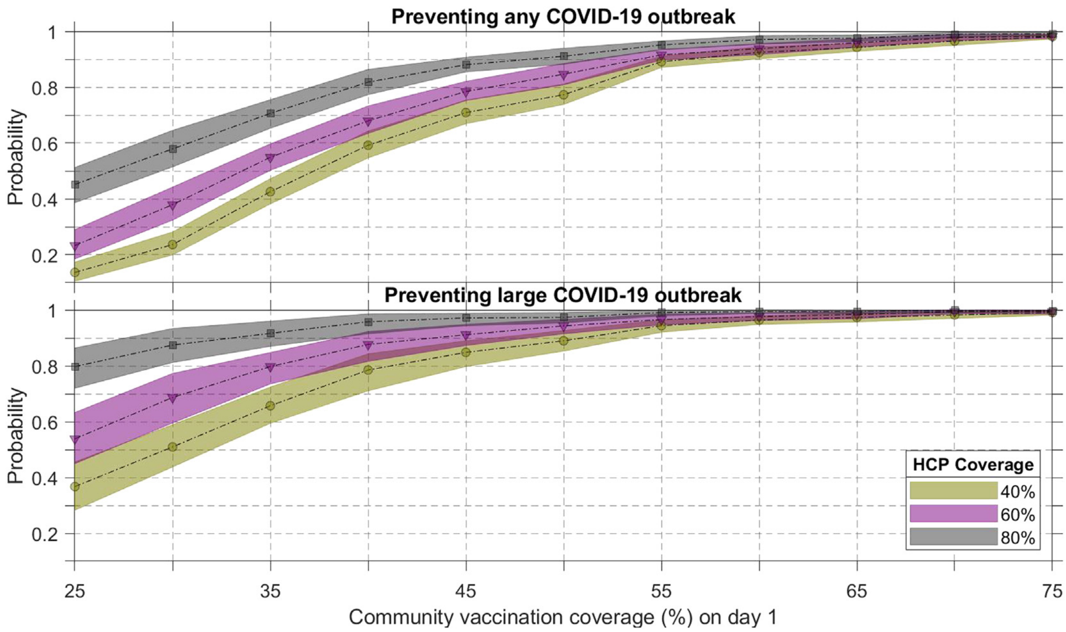

Fig. 3. Probability of preventing future COVID-19 outbreaks in the model nursing home (NH) increased with increase in vaccination coverage in the community or in healthcare personnel (HCP). We defined an outbreak and a large outbreak, respectively, as ≥1 and ≥5 symptomatic cases in residents or HCP. A probability value (shown by a point marker) and 90% confidence interval around it (shown by the width of a color band) at a given pair of community and HCP vaccination coverages was calculated by combining all model outputs from 9 sets (i.e., three facility-level adherence values for using recommended personal protective equipment by HCP X three resident vaccination coverage levels) of model simulations. These results are from model simulations performed with no facility-wide asymptomatic testing of HCP nor facility-wide testing upon a COVID-19 case detection.

of influenza vaccine among healthcare staff on reducing mortality and morbidity in residents as well as reducing stress on healthcare services in care homes [45,46]. Although we did not perform any analysis to account for high versus low COVID-19 prevalence in the community, increasing vaccination coverages among HCP may also protect nursing home residents in the surrounding communities with high COVID-19 prevalence [43].

This study investigated the transmission of SARS-CoV-2 in the facility under two testing strategies, and demonstrates that the default testing strategy (symptomatic testing of residents and HCP, as well as routine testing of asymptomatic HCP and facility-wide screening upon detecting a case) is expected to produce fewer cases among residents than an alternative testing strategy without asymptomatic testing or screening, which is consistent with existing guidelines [9,10] and previous modeling studies [12–14]. However, at high vaccination coverage scenarios (either high vaccination coverages in a nursing home or in its surrounding community, or a combination thereof), testing asymptomatic residents and staff may have limited value: the difference in the main outcome (Table 2) or in the secondary outcome (Fig. 3) was found to be negligible. This inference is consistent with the findings for medium and high vaccine efficacy scenarios reported previously [14].

We also explored the effect of adherence to recommended PPE use by HCP in the facility. Expected numbers of cumulative symptomatic cases in residents and uncertainty around them reduced as adherence level increased from low (25%) to high (75%) across the two testing strategies considered in this modeling exercise. When adherence to the recommended PPE was high, the effect on resident cases was more pronounced at low to medium vaccination coverages in the nursing home. This suggests that high adherence to recommended PPE may limit the size of future outbreaks. This is consistent with the findings of an observational study [47] that high vaccination coverage among nursing home resident and staff, together with continued use of recommended PPE and other IPC measures, is likely to protect unvaccinated persons in nursing homes [47].

In our sensitivity analysis, we found that a 25% relative reduction in VE (against infection) alone may not significantly impact the control efforts for COVID-19 outbreaks in nursing homes. However, when this reduction in VE against infection is combined either with halved VE against severe disease and halved VE against onward transmission (Supplementary Material Appendix 2 Figures S2E1 – S2E3) or with a 50% or greater increase in the transmissibility of SARS-CoV-2 (Supplementary Material Appendix 2 Figures S2F1 – S2G3), the risk of infection may be significantly elevated when vaccination coverage is low in either the nursing home or in the surrounding community. While lower rates of adherence to infection control strategies, including PPE implementation, are one potential cause of increased transmissibility, SARS-CoV-2 variants of concern such as the Delta or Omicron variant, also can increase the virus's transmissibility. Studies show that the Delta variant is twice as transmissible as the wildtype lineage [48,49].

An emerging variant of SARS-CoV-2 (e.g., the Omicron variant) may be more transmissible than the Delta variant among fully vaccinated persons due to immune evasion [50]. Our sensitivity analysis with reduced values of all three VEs (results shown in Supplementary Material Appendix 2 Figures S2E1 – S2E3) describing such a scenario where we found COVID-19 cases among nursing home residents were likely to increase (Supplementary Material Appendix 2 Figures S2E1 – S2E3). There is substantial uncertainty in these emerging variant scenarios. The results from a limited sensitivity analysis on equal infectiousness of breakthrough infections also showed increased uncertainty in the expected resident cases under our parsimonious assumption of equal infectiousness of symptomatic and asymptomatic infected persons (Supplementary Material Appendix 2 Figure S2I).

In our compartment-based model, the underlying assumption behind contacts or interactions between individuals is homogeneous. Unlike an individual-based model [14], our model may not capture heterogeneities in resident-HCP contact patterns (e.g., some residents may need more frequent care by HCP than others) or community interactions. This homogeneity assumption may have little impact on our inference. This is because our model simulations were carried out stochastically, which allowed us to report uncertainty around the expected numbers of COVID-19 cases in nursing home residents. Second, our nursing home model is a single-bed occupancy nursing home. It may not represent those of US nursing homes, which operate on a mix of single-bed with double-bed or quadruple-bed occupancy for increasing healthcare cost-efficiency [8,51]. This reality could be another cause of increased transmissibility, which was not accounted for in our models. Although we would expect SARS-CoV-2 to transmit more efficiently in more crowded facilities [8], the key qualitative finding of this analysis is that high vaccination coverage in nursing homes and in their surrounding communities may prevent future COVID-19 outbreaks. This is because increased crowding is likely not associated with the probability of COVID-19 introduction [8]. Third, waning immunity (either from natural infection or from vaccine) was not considered in this model. Since the outcomes are presented over a six-month simulation period (or less in the reporting of estimates of the probability of preventing outbreaks), not including waning of protection in the model is unlikely to have major impact on the results. This is because any decrease in VE against infection or severe disease has been significantly low over a six-month period in fully vaccinated persons [25]. Finally, the model was not parameterized by fitting its outputs to reported cases from a 100-bed US nursing home, with known staff-to-resident ratio. This may make our findings not directly comparable to outcomes in a real 100-bed care facility using similar infection prevention measures. In this exercise, our focus was to investigate the role of high vaccination coverage among nursing home residents and HCP, with rise in COVID-19 vaccination coverage in the surrounding communities of nursing homes. Some of these aforementioned limitations may be a focus of our future nursing home modeling exercises.

5. Conclusion

Our results suggest that increasing community vaccination coverage leads to fewer COVID-19 cases among care home residents, along with low probability (<5%) of a large COVID-19 outbreak at community coverage of 60% and above (Fig. 3). When vaccination coverage in the community and among nursing residents and staff was 60% or higher, regular asymptomatic staff screening and facility-wide testing had practically no additional benefit in terms of reducing cases among residents and staff. This finding suggests that de-escalation of facility-wide regular testing of asymptomatic residents and staff may be feasible, provided vaccination coverage in nursing homes as well as in their surrounding communities remains high.

6. Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the views and the official position of the Centers for Disease Control and Prevention.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.vaccine.2022.04.040.

References

[1] Comas-Herrera A et al. Mortality associated with COVID-19 in care homes: international evidence. Article in LTCcovid.org. International Long-Term Care Policy Network, CPEC-LSE 2020;14.

[2] Centers for Medicare and Medicaid Services. COVID-19 Nursing Home Data: Resident and Staff Cases and Deaths; 2021 [cited 2021 30 May]; Available from: https://data.cms.gov/stories/s/bkwz-xpvg.

[3] Centers for Disease Control and Prevention. COVID Data Tracker. 2021 [cited 2021 2 September]; Available from: https://covid.cdc.gov/covid-data-tracker/#datatracker-home.

[4] Christie A, Henley SJ, Mattocks L, Fernando R, Lansky A, Ahmad FB, et al. Decreases in COVID-19 Cases, Emergency Department Visits, Hospital Admissions, and Deaths Among Older Adults Following the Introduction of COVID-19 Vaccine - United States, September 6, 2020-May 1, 2021. MMWR Morb Mortal Wkly Rep 2021;70(23):858–64.

[5] Benin AL, Soe MM, Edwards JR, Bagchi S, Link-Gelles R, Schrag SJ, et al. Ecological analysis of the decline in incidence rates of COVID-19 among nursing home residents associated with vaccination, United States, December 2020-January 2021. J Am Med Direct Associat 2021;22(10):2009–15.

[6] Centers for Medicare and Medicaid Services. COVID-19 Nursing Home Data: Percent of Current Residents and Staff with COVID-19 Vaccinations; 2021 [cited 2021 May 30]; Available from: https://data.cms.gov/stories/s/bkwz-xpvg.

[7] Bagchi S, Mak J, Li Q, Sheriff E, Mungai E, Anttila A, et al. Rates of COVID-19 among residents and staff members in nursing homes - United States, May 25-November 22, 2020. MMWR Morb Mortal Wkly Rep 2021;70(2):52–5.

[8] Brown KA, Jones A, Daneman N, Chan AK, Schwartz KL, Garber GE, et al. Association between nursing home crowding and COVID-19 infection and mortality in Ontario, Canada. JAMA Internal Med 2021;181(2):229. https://doi.org/10.1001/jamainternmed.2020.6466.

[9] Centers for Disease Control and Prevention. Interim Infection Prevention and Control Recommendations to Prevent SARS-CoV-2 Spread in Nursing Homes; 2021 [cited 2021 11 June]; Available from: https://www.cdc.gov/coronavirus/2019-ncov/hcp/nursing-homes-testing.html.

[10] WHO. Infection prevention and control guidance for long-term care facilities in the context of COVID-19: interim guidance, 8 January 2021; 2021, World Health Organization. p. 16.

[11] Holmdahl I, Kahn R, Hay JA, Buckee CO, Mina MJ. Estimation of transmission of COVID-19 in simulated nursing homes with frequent testing and immunity-based staffing. JAMA Netw Open 2021;4(5):e2110071. https://doi.org/10.1001/jamanetworkopen.2021.10071.

[12] See I et al. Modeling effectiveness of testing strategies to prevent COVID-19 in nursing homes -United States, 2020. Clin Infect Dis 2021.

[13] Roselló A. et al., Impact of non-pharmaceutical interventions on SARS-CoV-2 outbreaks in English care homes: a modelling study. medRxiv; 2021.

[14] Kahn R et al. Mathematical modeling to inform vaccination strategies and testing approaches for COVID-19 in nursing homes. Clin Infect Dis 2021.

[15] Telford CT et al. COVID-19 Infection prevention and control adherence in long-term care facilities, Atlanta, Georgia. J Am Geriatr Soc 2021;69(3):581–6.

[16] Li Y, Fang F, He M. Exploring the N95 and Surgical Mask Supply in U.S. Nursing Homes During COVID-19. J Appl Gerontol 2021;40(3):257–62.

[17] Jones K, Mantey J, Washer L, Meddings J, Patel PK, Montoya A, et al. When planning meets reality: COVID-19 interpandemic survey of Michigan Nursing Homes. Am J Infect Control 2021;49(11):1343–9.

[18] Xu H, Intrator O, Bowblis JR. Shortages of staff in nursing homes during the COVID-19 pandemic: what are the driving factors? J Am Med Direct Associat 2020;21(10):1371–7.

[19] Pei S, Kandula S, Shaman J. Differential effects of intervention timing on COVID-19 spread in the United States. Sci Adv 2020;6(49). p. eabd6370.

[20] Zhang, Y. et al., The real time effective reproductive number for COVID-19 in the United States. medRxiv; 2020: p. 2020.05.08.20095703.

[21] Keeling MJ, Rohani P. Modeling infectious diseases in humans and animals. Princeton, New Jersey: Princeton University Press; 2008. p. 366.

[22] Centers for Medicare and Medicaid Services. Minimum Data Set 3.0 Public Reports; 2021.

[23] Dinnes J et al. Rapid, point-of-care antigen and molecular-based tests for diagnosis of SARS-CoV-2 infection. Cochrane Database Syst Rev 2021;3(3). p. Cd013705.

[24] McKay SL, Tobolowsky FA, Moritz ED, Hatfield KM, Bhatnagar A, LaVoie SP, et al. Performance Evaluation of Serial SARS-CoV-2 Rapid Antigen Testing During a Nursing Home Outbreak. Ann Intern Med 2021;174(7):945–51.

[25] Centers for Disease Control and Prevention. Science Brief: COVID-19 Vaccines and Vaccination. Science Briefs [Web content] 2021 [cited 2021 7 May]; Available from: https://www.cdc.gov/coronavirus/2019-ncov/science/science-briefs/fully-vaccinated-people.html.

[26] Tenforde MW. Effectiveness of Pfizer-BioNTech and Moderna Vaccines Against COVID-19 Among Hospitalized Adults Aged≥ 65 Years—United States, January–March 2021. MMWR Morb Mort Wkly Report; 2021. **70**.

[27] Pilishvili T., et al., Interim estimates of vaccine effectiveness of Pfizer-BioNTech and Moderna COVID-19 vaccines among health care personnel—33 US sites, January–March 2021. Morb Mort Wkly Rep; 2021. **70**(Early Release).

[28] Thompson MG 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 US locations, December 2020–March 2021. Morb Mortal Wkly Rep 2021;70(13):495.

[29] Pawlowski C et al. FDA-authorized COVID-19 vaccines are effective per real-world evidence synthesized across a multi-state health system. medRxiv 2021. p. 2021.02.15.21251623.

[30] Eyre DW. et al., The impact of SARS-CoV-2 vaccination on Alpha & Delta variant transmission. medRxiv; 2021: p. 2021.09.28.21264260.

[31] Braeye T, Cornelissen L, Catteau L, Haarhuis F, Proesmans K, De Ridder K, et al. Vaccine effectiveness against infection and onwards transmission of COVID-19: Analysis of Belgian contact tracing data, January-June 2021. Vaccine 2021;39(39):5456–60.

[32] Prunas O. et al., Vaccination with BNT162b2 reduces transmission of SARS-CoV-2 to household contacts in Israel. medRxiv; 2021: p. 2021.07.13.21260393.

[33] Harris RJ, Hall JA, Zaidi A, Andrews NJ, Dunbar JK, Dabrera G. Effect of vaccination on household transmission of SARS-CoV-2 in England. N Engl J Med 2021;385(8):759–60.

[34] Levine-Tiefenbrun M, Yelin I, Katz R, Herzel E, Golan Z, Schreiber L, et al. Initial report of decreased SARS-CoV-2 viral load after inoculation with the BNT162b2 vaccine. Nat Med 2021;27(5):790–2.

[35] Marks M, Millat-Martinez P, Ouchi D, Roberts Ch, Alemany A, Corbacho-Monné M, et al. Transmission of COVID-19 in 282 clusters in Catalonia, Spain: a cohort study. Lancet Infect Dis 2021;21(5):629–36.

[36] Pineles L, Petruccelli C, Perencevich EN, Roghmann M-C, Gupta K, Cadena J, et al. The impact of isolation on healthcare worker contact and compliance with infection control practices in nursing homes. Infect Control Hosp Epidemiol 2018;39(6):683–7.

[37] Centers for Medicare and Medicaid Services, Trump Administration Issues Key Recommendations to Nursing Homes, State and Local Governments; 2020. p. 3.

[38] McGarry BE, Grabowski DC, Barnett ML. Severe staffing and personal protective equipment shortages faced by nursing homes during The COVID-19 pandemic. Health Aff 2020;39(10):1812–21.

[39] Denny-Brown N et al. Covid-19 intensifies nursing home workforce challengesUS. Department of Health and Human Services Assistant Secretary for Planning and Evaluation Behavioral Health, Disability, and Aging Policy, 2020.

[40] Scobie H. Update on Emerging SARS-CoV-2 Variants and COVID-19 vaccines; 2021 [cited 2021 14 Aug 2021]; Available from: https://www.cdc.gov/vaccines/acip/meetings/downloads/slides-2021-08-13/04-COVID-Scobie-508.pdf.

[41] Lopez Bernal J., et al. Effectiveness of COVID-19 vaccines against the B. 1.617. 2 (Delta) variant. New England Journal of Medicine; 2021.

[42] McEvoy D, McAloon C, Collins A, Hunt K, Butler F, Byrne A, et al. Relative infectiousness of asymptomatic SARS-CoV-2 infected persons compared with symptomatic individuals: a rapid scoping review. BMJ Open 2021;11(5): e042354. https://doi.org/10.1136/bmjopen-2020-042354.

[43] McGarry BE, Barnett ML, Grabowski DC, Gandhi AD. Nursing Home Staff Vaccination and Covid-19 Outcomes. N Engl J Med 2022;386(4):397–8.

[44] McGarry BE, Shen K, Barnett ML, Grabowski DC, Gandhi AD. Association of nursing home characteristics with staff and resident COVID-19 vaccination coverage. JAMA Int Med 2021;181(12):1670. https://doi.org/10.1001/jamainternmed.2021.5890.

[45] Hayward AC et al. Effectiveness of an influenza vaccine programme for care home staff to prevent death, morbidity, and health service use among residents: cluster randomised controlled trial. BMJ 2006;333(7581):1241.

[46] Lemaitre M, Meret T, Rothan-Tondeur M, Belmin J, Lejonc J-L, Luquel L, et al. Effect of influenza vaccination of nursing home staff on mortality of residents: a cluster-randomized trial. J Am Geriatr Soc 2009;57(9):1580–6.

[47] White EM, Yang X, Blackman C, Feifer RA, Gravenstein S, Mor V. Incident SARS-CoV-2 infection among mRNA-vaccinated and unvaccinated nursing home residents. N Engl J Med 2021;385(5):474–6.

[48] Campbell F, Archer B, Laurenson-Schafer H, Jinnai Y, Konings F, Batra N, et al. Increased transmissibility and global spread of SARS-CoV-2 variants of concern as at June 2021. Eurosurveillance 2021;26(24). https://doi.org/10.2807/1560-7917.ES.2021.26.24.2100509.

[49] Dhar Mahesh, S., et al., Genomic characterization and epidemiology of an emerging SARS-CoV-2 variant in Delhi, India. Science. **0**(0): p. eabj9932.

[50] Lyngse FP et al. SARS-CoV-2 Omicron VOC Transmission in Danish Households. medRxiv 2021. p. 2021.12.27.21268278.

[51] Calkins M, Cassella C. Exploring the cost and value of private versus shared bedrooms in nursing homes. The Gerontologist 2007;47(2):169–83.