Infection Control & Hospital Epidemiology (2023), **44**, 1987–1994
doi:10.1017/ice.2023.94

SHEA

Original Article

Twice weekly polymerase chain reaction (PCR) surveillance swabs are not as effective as daily antigen testing for containment of severe acute respiratory coronavirus virus 2 (SARS-CoV-2) outbreaks: A modeling study based on real world data from a child and adolescent psychiatry clinic

Sara Grundel PhD[1], Hans-Henning Flechtner MD[2], Jana Butzmann MD[3], Peter Benner PhD[1] and Achim J. Kaasch MD[3]

[1]Computational Methods in Systems and Control Theory, Max Planck Institute for Dynamics of Complex Technical Systems, Magdeburg, Germany, [2]Department of Child and Adolescent Psychiatry, Psychotherapy and Psychosomatic Medicine, Medical Faculty, Otto von Guericke University Magdeburg, Magdeburg, Germany and [3]Institute of Medical Microbiology and Hospital Hygiene, Medical Faculty, Otto von Guericke University Magdeburg, Magdeburg, Germany

Abstract

Objective: In the coronavirus disease 2019 (COVID-19) pandemic, child and adolescent psychiatry wards face the risk of severe acute respiratory coronavirus 2 (SARS-CoV-2) introduction and spread within the facility. In this setting, mask and vaccine mandates are hard to enforce, especially for younger children. Surveillance testing may detect infection early and enable mitigation measures to prevent viral spread. We conducted a modeling study to determine the optimal method and frequency of surveillance testing and to analyze the effect of weekly team meetings on transmission dynamics.

Design and setting: Simulation with an agent-based model reflecting ward structure, work processes, and contact networks from a real-world child and adolescent psychiatry clinic with 4 wards, 40 patients, and 72 healthcare workers.

Methods: We simulated the spread of 2 SARS-CoV-2 variants over 60 days under surveillance testing with polymerase chain reaction (PCR) tests and rapid antigen tests in different scenarios. We measured the size, peak, and the duration of an outbreak. We compared medians and percentage of spillover events to other wards from 1,000 simulations for each setting.

Results: The outbreak size, peak, and duration were dependent on test frequency, test type, SARS-CoV-2 variant, and ward connectivity. Under surveillance conditions, joint staff meetings and therapists shared between wards did not significantly change median outbreak size under surveillance conditions. With daily antigen testing, outbreaks were mostly confined to 1 ward and median outbreak sizes were lower than with twice-weekly PCR testing (1 vs 22; $P < .001$).

Conclusion: Modeling can help to understand transmission patterns and guide local infection control measures.

(Received 8 November 2022; accepted 19 April 2023; electronically published 10 July 2023)

The coronavirus disease 2019 (COVID-19) pandemic has considerable impact on healthcare systems worldwide. It has caused considerable morbidity and mortality, with >500 million registered cases and 6 million deaths worldwide.[1] Additionally, symptoms can persist or reemerge after the acute infection.[2] Although morbidity and mortality rates in children and adolescents are generally lower than in adults, potentially fatal hyperinflammatory disorders called pediatric inflammatory multisystem syndrome temporally associated with COVID-19 (PIMS-TS) and multisystem inflammatory syndrome associated with COVID-19 (MIS-C) have been described.[3]

In the hospital setting, severe acute respiratory coronavirus virus 2 (SARS-CoV-2) poses a risk for healthcare workers and patients alike. Stringent infection control measures are necessary to prevent SARS-CoV-2 introduction and spread. Many hospitals have introduced surveillance testing for staff and patients, FFP2/N95 mask mandates for healthcare personnel and patients (whenever possible), organizational changes to reduce contacts between staff (limited unmasked contact during breaks), and between staff and

Corresponding author: Achim J. Kaasch; Email: Achim.kaasch@med.ovgu.de

Cite this article: Grundel S, Flechtner H-H, Butzmann J, Benner P, Kaasch AJ. Twice weekly polymerase chain reaction (PCR) surveillance swabs are not as effective as daily antigen testing for containment of severe acute respiratory coronavirus virus 2 (SARS-CoV-2) outbreaks: A modeling study based on real world data from a child and adolescent psychiatry clinic. *Infect Control Hosp Epidemiol* 2023. 44: 1987–1994, doi: 10.1017/ice.2023.94

patients. Positive patients are isolated and positive staff are banned from work. Furthermore, some countries (eg, France, Italy, Germany) implemented vaccine mandates for healthcare personnel.

In the setting of child and adolescent psychiatry, there are major challenges for infection control. A mask mandate for children aged <6 years is neither practical nor desirable since facial expressions play a much more important role in communication with children than with adults.[4,5]

Limiting the contact between patients would prevent therapy in certain situations and seems infeasible given the therapeutic approaches used on an inpatient ward such as psychotherapy including parental guidance, play therapy, and particularly group therapy as well as multifamily therapy.[6] Reducing the number of patients in a ward would mean that fewer patients can be admitted, which counteracts the higher need for patient care during the pandemic.[7]

Children have a higher rate of asymptomatic or oligosymptomatic infection,[8] which reduces the chance of detecting infection based on symptoms. Therefore, surveillance testing is highly relevant in child and adolescent psychiatry wards.

Little evidence indicates how often surveillance testing for staff and patients should be done and which type of test should be used. Generally, 2 types of tests with different test characteristics are available. Rapid antigen tests yield a result within 15–30 minutes, but they have lower test performance, especially regarding sensitivity.[9] Polymerase chain reaction (PCR) tests are the gold standard for SARS-CoV-2 testing, and results can be obtained in <1 hour, but the usual time to reporting is ≥24 hours in many settings.

The individual contribution of time to reporting and test accuracy to successful mitigation of an outbreak is unclear. A simulation of a nursing home with 100 staff and residents suggested that daily antigen testing is superior to PCR testing with a time to reporting of 2 days.[10] An epidemiological simulation of repeated population screening prioritized time to reporting over test sensitivity.[11] In a study of surveillance testing in 1,931 asymptomatic athletes, daily antigen testing was equivalent to PCR testing 2–3 times per week.[12] However, in a modeling study, the benefits of surveillance testing were mostly negated if accompanied by decreased infection control practice.[13]

Pandemics occur in waves with large regional differences. A particular challenge in the COVID-19 pandemic is the co-occurrence of SARS-CoV-2 variants with different epidemiological characteristics such as the speed of spread, incubation time, and viral load. For example, the SARS-CoV-2 omicron variant has drastically changed the dynamics of spread within the South African population compared to the previous delta variant.[14] These factors complicate the prediction of future waves based on observational studies.

Modeling studies can help fill this gap because they can easily be adapted to the different characteristics of a virus variant. The 2 modeling frameworks employed in viral epidemics are compartmental models and agent-based models. Compartmental models are well suited for large populations, which are computationally expensive for agent-based models.[14] However, agent-based models consider a described set of agents and their connections, which is useful if that knowledge is specifically available. In the spatially delineated setting of a hospital ward, agent-based models can capture relevant interactions for transmission. They allow researchers to vary the individual agent's behavior in the model and to explore its effects on disease transmission in different scenarios.[15]

We report a modeling study to assess the optimal frequency of SARS-CoV-2 surveillance testing in the setting of a child and adolescent psychiatry clinic. Using an agent-based model, we simulated the transmission of SARS-CoV-2 within the contact networks of healthcare personnel and patients. Different testing strategies were assessed through repeated simulations, and the likelihood and size of an outbreak were estimated. We further estimated the effect of weekly meetings on transmission dynamics.

Methods

Structure of the child and adolescent clinic

We created an agent-based model reproducing the structure and work processes of the child and adolescent psychiatric clinic in Magdeburg, Germany, under pandemic conditions. The clinic consisted of 4 separate wards, with a multidisciplinary team. Each team consisted of 14 nurses and 3 doctors who were responsible for 10 patients. Additional personnel included 4 therapists from various professions: psychologists, occupational therapists, music therapists, and play therapists. During the pandemic, we restructured the wards so that each ward constituted a separate "family unit." Team conferences across wards were reduced to an absolute minimum or were conducted via videoconferencing. Therapists, who usually work on different wards, were allocated to just 1 ward, whenever possible.

Within a given ward, patients and staff were closely connected and transmission of SARS-CoV-2 could occur. The spread from one ward to another was less likely because spread could only occur through common staff, such as therapists, or through meetings of other staff members across wards.

Model and scenario setup

The model was programmed in MATLAB (MATLAB and Statistics Toolbox Release 2021a, The MathWorks, Natick, MA). Up to 112 agents were connected based on a graph version of the clinic structure (Fig. 1). Each node represented an agent (ie, a person). An edge connecting 2 nodes represented a face-to-face contact associated with a transmission probability. Different scenarios, regarding intervention strategies, meeting frequencies, and involvement of therapists on the wards, were set by varying the graph structure (cf, connection between nodes) and edge weights (cf, infection probabilities). Edges resulting from weekly meetings were only active on the day of the meeting.

We assessed 3 network setups with varying degree of interconnectivity, reflecting possible interventions to reduce mixing of hospital staff. In the "separated" setup (I), there were no interconnections between the 4 different wards. In the "restricted" setup (II), we added weekly staff meetings between all doctors from the 4 wards but sessions by therapists were suspended. In the "regular" setup (III), therapists were connected with different individual children across all 4 wards and weekly staff meetings were held.

Within the different setups, we tested how variations in surveillance testing and SARS-CoV-2 variants affected transmission dynamics. To this end, we simulated scenarios with parameters reflecting a PCR test and a rapid antigen test. Rapid antigen testing was modeled with test sensitivities of 50%, 60%,

https://doi.org/10.1017/ice.2023.94 Published online by Cambridge University Press

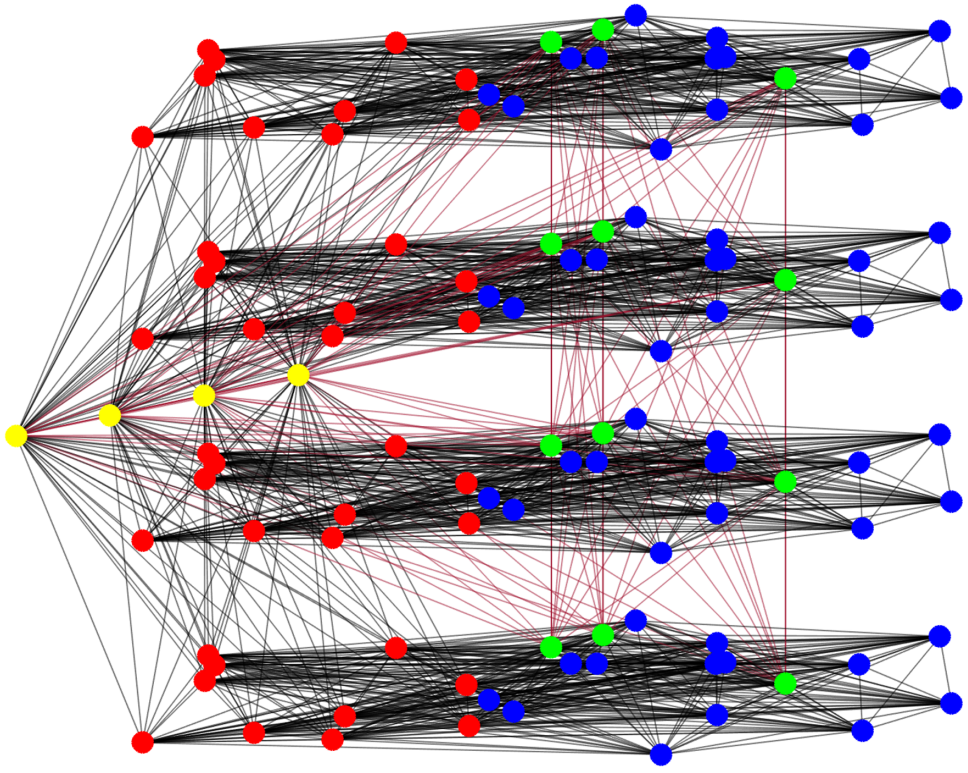

Figure 1. Contact network of a child and adolescent psychiatry clinic with 4 wards. Each dot (node) represents a person. Patients (red), doctors (green), nurses (blue), and therapists (yellow) are connected by a "strong" edge (grey). Additionally, doctors and therapists are connected by a "weak" edge (red), which denotes the connection through weekly meetings.

70%, and 80% for the delta variant and the omicron variant, as well as different frequencies of surveillance testing and different times to result (Table 1).

Outbreak simulation

We simulated different scenarios over 60 days with 1,000 simulations each. A simulation of 60 days was typically sufficient for transmission to stop, either by infecting every person or by having eliminated all infections.

At each run, we first initialized the model by setting the transmission probability (time dependent probability of infecting another person) of each agent to a random value from the probability distribution table. The distribution of probabilities for transmission and detection by either PCR- or antigen-test are shown in Figure 2 for the omicron variant (for the delta variant, see Supplementary Fig. 1 online). We chose parameters based on published data on symptom onset,[16–20] kinetics of viral load,[16,21,22] the rate of oligosymptomatic or asymptomatic persons,[19,21,23–25] the course of infectiousness,[16,18,20,26] and household transmission rate (Supplementary Table 1 online).[27–29] Then, we randomly selected an agent as the index case and a weekday as the day when the infection was first introduced into the model. Depending on the scenario, network edges were added for therapists and staff meetings.

A time-stepping algorithm moved through each day and performed the following routine: (1) calculation of test results according to the test strategy; (2) removal of agents that tested positive (immediately for antigen tests, the day after for PCR, and 2 days after for the scenario with a delayed PCR reporting), leading to fewer agents in the system; and (3) computation of newly exposed neighbors according to transmission probability of the individual multiplied by the edge transmission (0.21 for the delta variant and 0.31 for the omicron variant).

Model calibration and validation

To calibrate the model, we plotted transmission rate, connectivity, number of runs against outbreak size and visually confirmed continuity of outcome variables (Supplementary Fig. 4 online). Furthermore, we checked whether outcome parameters were within the possible range. To validate the model, we checked model output for plausibility; however, no real-world data were available for a full model validation.

Analyses

For each testing scenario, we assessed the total number of infected persons (outbreak size), the maximum number of persons infected on one day (outbreak peak), and the number of days until the last person was infected (outbreak duration) as outcome measures. The Kruskal-Wallis test was used to test for statistical significance for continuous variables.

Results

As a baseline, we first simulated transmission dynamics for the SARS-CoV-2 delta and omicron variants without any surveillance testing for the 3 network setups: separated, restricted, and regular (Fig. 3). In the separated setting, wards were not connected, and the maximum outbreak size was 27, which means that all staff and patients of the ward were infected. Outbreaks with the omicron variant were faster and more intense than with the delta variant. The maximum outbreak size was reached in 88% for the omicron variant and in 57% for the delta variant. The average outbreak size

https://doi.org/10.1017/ice.2023.94 Published online by Cambridge University Press

Table 1. Overview of the Scenarios Simulated. The Network Setup was Either "Separated" (I), "Restricted" (II), or "Regular" (III)

ID No.	Model Scenario	Network Setup	Test	Test frequency (No. of Days Between Tests)	SARS-CoV-2 Variant Characteristics	Figure(s)
1	Delta, no test strategy	I–III	None (0)	. . .	Delta (a)	3
2	Omicron, no test strategy	I–III	None (0)	. . .	Omicron (b)	3
3	Delta, antigen	I–III	Antigen (1)	1, 2, 3, 4, 5, 6, 7, 8, 9	Delta (a)	2, 3 Suppl
4	Omicron, antigen	I–III	Antigen (1)	1, 2, 3, 4, 5, 6, 7, 8, 9	Omicron (b)	4, 5, 6
5	Delta, PCR	I–III	PCR (2)	1, 2, 3, 4, 5, 6, 7, 8, 9	Delta (a)	2, 3 Suppl
6	Omicron, PCR	I–III	PCR (2)	1, 2, 3, 4, 5, 6, 7, 8, 9	Omicron (b)	4, 5, 6

Note. PCR, polymerase chain reaction.

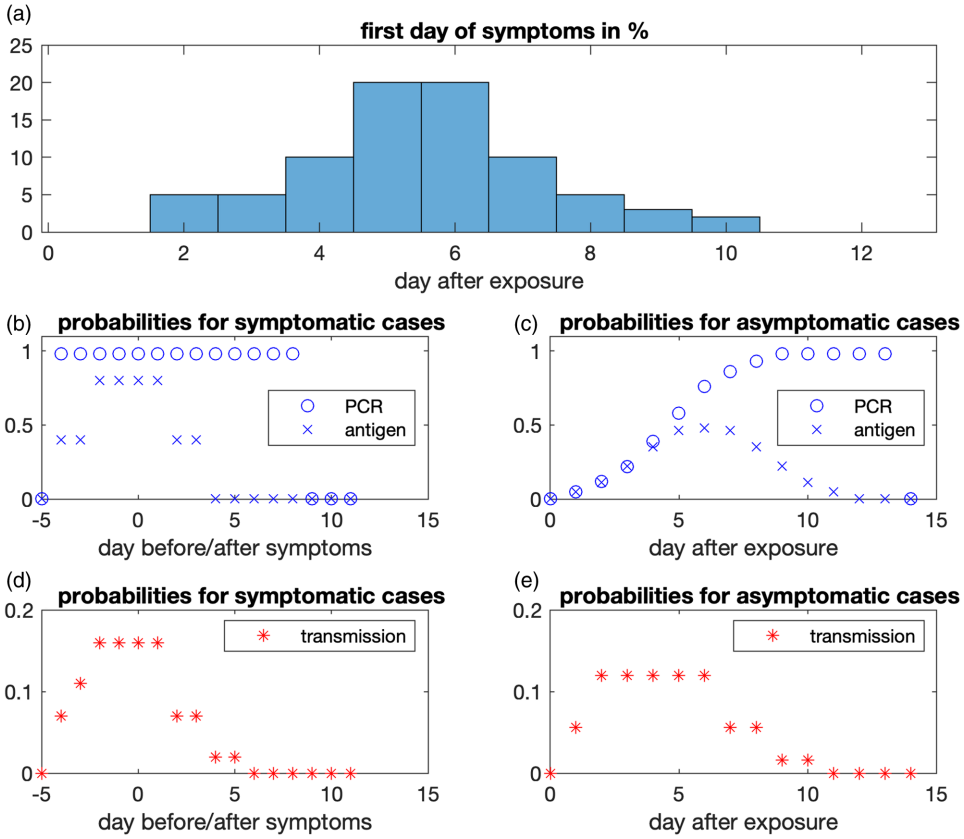

Figure 2. Parameters of transmission kinetics for the SARS-CoV-2 omicron variant. (a) Distribution of time to first symptom after exposure; 20% of cases were assumed to be asymptomatic. (b) Distribution of the probability for transmission and for a positive test result from start of symptoms. (c) Distribution of transmission and distribution of a positive test result for asymptomatic cases from day after exposure. Note. Polymerase chain reaction test (o), antigen test (x), and transmission (*).

was 26 versus 24 ($P = $ e-50), and the average outbreak duration was 30 days versus 38 days ($P < .001$), respectively.

Similar dynamics were identified for other network settings. In the restricted setting, wards were connected by regular staff meetings. Outbreak size was significantly higher with the SARS-CoV-2 omicron variant versus the delta variant (median, 55 vs 28; $P < .001$). For the omicron variant, 72% of outbreaks extended to 1 or more other wards, 55% of outbreaks extended to >2 wards, and 36% of outbreaks extended to all 4 wards.

In the regular setting, wards were additionally connected by shared therapists. In this scenario, with the SARS-CoV-2 omicron variant, 87% of outbreaks extended to 1 or more other wards, 84% of outbreaks extended to >2 wards, and 80% of outbreaks extended to all 4 wards were affected for the omicron variant. The median outbreak size was 111 in the regular setting versus 55 ($P < .001$) in the restricted setting.

Surveillance PCR testing in a frequency of up to 1 test every 9 days showed a smaller size, shorter duration, and lower outbreak peak compared to the setting without surveillance tests (Fig. 4).

Interestingly, we observed a higher median outbreak size in the restricted and regular settings at a test frequency of every 7 days compared to every 6 or 8 days for PCR testing (Fig. 4). This finding is related to the fact that regular meetings of staff between wards were scheduled every 7 days on Mondays, whereas the weekday of PCR testing varied between simulations.

Antigen tests showed a lower effect than PCR testing in all 3 performance measures. Increased testing frequency as well as increased test sensitivity led to a decreased outbreak duration, outbreak peak, and outbreak size (Fig. 4, Supplementary Fig. 2 online for the delta variant).

For both SARS-CoV-2 variants, rapid antigen testing with at least 80% sensitivity could prevent extension of the outbreak to

https://doi.org/10.1017/ice.2023.94 Published online by Cambridge University Press

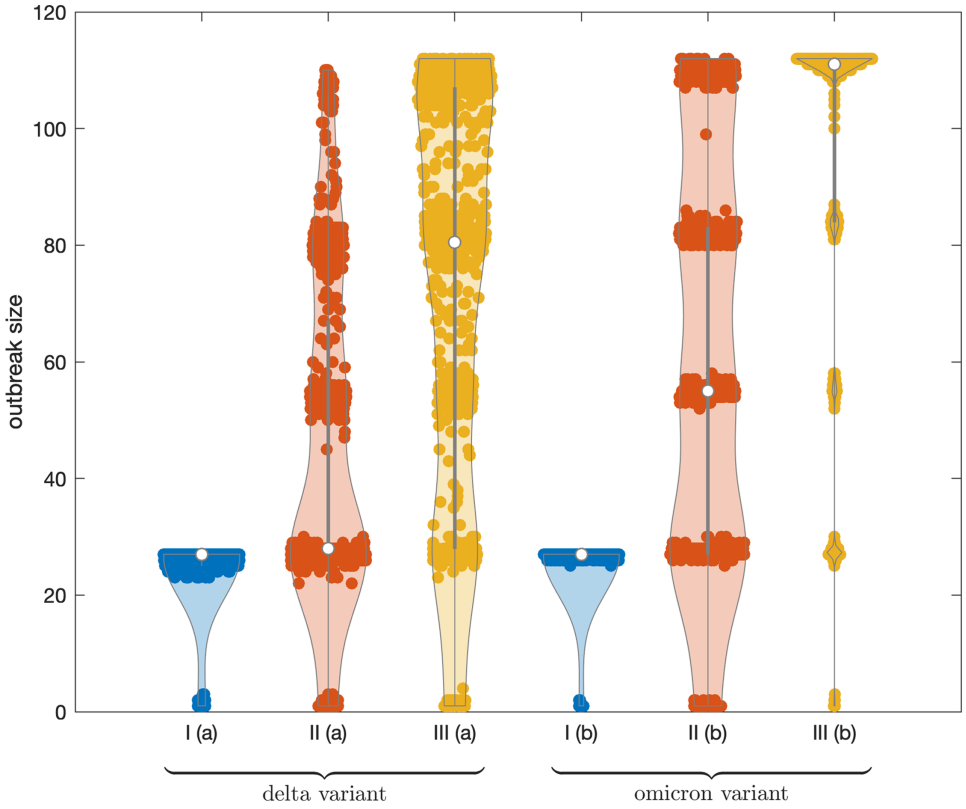

Figure 3. Outbreak size without containment through surveillance. Violin plots of 1,000 simulations of outbreak size for the 3 network setups, separated (I), restricted (II), and regular (III) for the SARS-CoV-2 delta variant (a) and the omicron variant (b) when no test strategy was implemented.

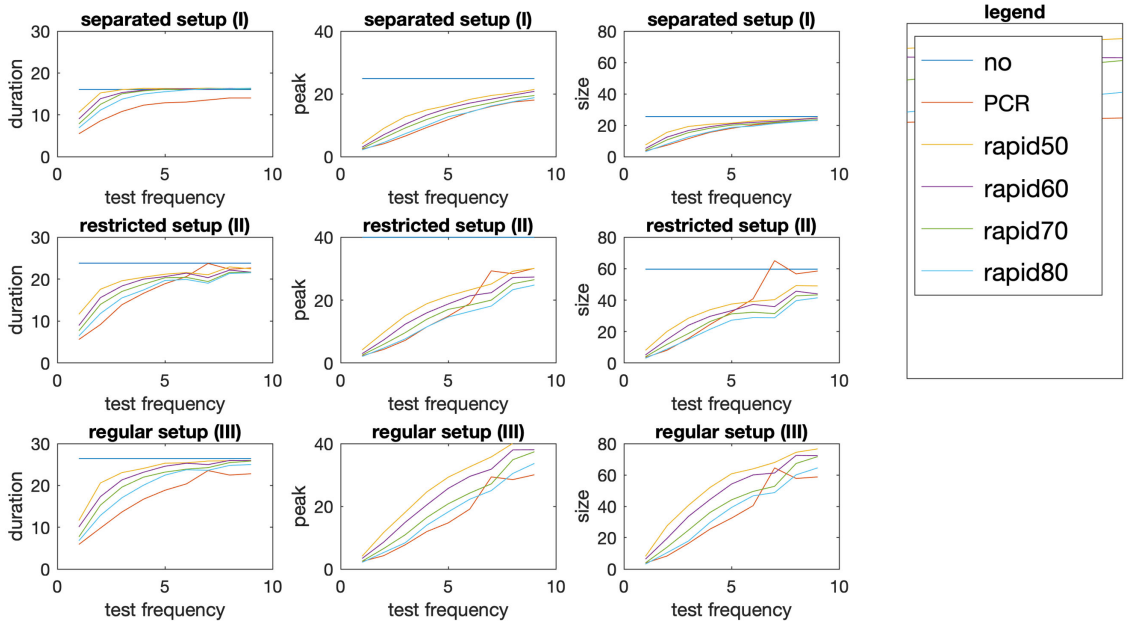

Figure 4. Influence of test frequency on outbreak duration (left panels), peak (middle panels), and size of the outbreak (right panels) in the separated (I), restricted (II), and regular (III) setup. The colored lines denote polymerase chain reaction (PCR) test and rapid antigen tests with different sensitivities (50%, 60%, 70%, and 80%). All data are for the SARS-CoV-2 omicron variant.

other wards in 99% of cases with a test frequency of every day or every other day. Outbreaks were small with a median outbreak size of <5 (Figs. 5 and 3 and Supplementary Table 2 online).

Under surveillance conditions, increased connectivity between wards by adding weekly meetings and cross-ward therapists did not significantly change transmission dynamics. The median outbreak size was 1 in both cases ($P = .214$), when comparing the restricted versus the regular setting with daily antigen testing and median outbreak in the separated setting was also 1 with $P = .277$ and $P = .865$ compared with the regular and restricted setting.

Comparing typical test frequencies for antigen tests and PCR tests, the median outbreak size was 1 for daily rapid antigen testing

https://doi.org/10.1017/ice.2023.94 Published online by Cambridge University Press

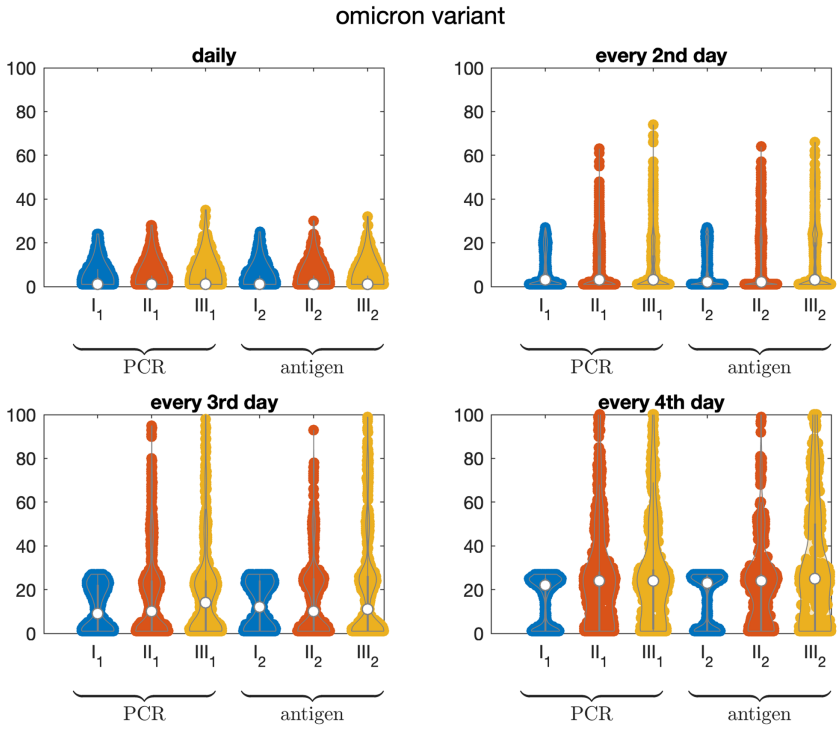

Figure 5. Outbreak size for 2 testing frequencies (every day to every 4 days). Simulations were performed for the SARS-CoV-2 omicron variant with 3 network setups, that is, separated (I), restricted (II), and regular (III), polymerase chain reaction test (1), and rapid antigen tests with 80% sensitivity (2).

and 3 for every-other-day testing in the regular setting for the SARS-CoV-2 omicron variant. For PCR testing every other day, the median outbreak size was 3 and for twice-weekly PCR testing, the median outbreak size was 22 ($P < .001$ for daily antigen testing versus twice weekly PCR testing) (Fig. 6). Therefore, twice-weekly PCR testing was inferior to daily antigen testing and was not sufficient to confine an outbreak to a single ward in 30% of cases.

A shorter time to reporting the test result reduced outbreak size. Twice-weekly PCR testing with a time to reporting of 2 days showed a median outbreak size of 46, whereas a time to reporting of 1 day showed a median outbreak size of 22 ($P < .001$) (Fig. 6).

Discussion

In the hospital setting, surveillance testing can help to detect SARS-CoV-2 introduction into a clinical ward, and subsequent isolation of patients and/or staff can block transmission. In this study, we modeled a child and adolescent psychiatry clinic and demonstrated that the impact on outbreak size and duration depends on test frequency, sensitivity of tests, time to reporting the test results, and the SARS-CoV-2 variant. Under surveillance conditions, weekly meetings and cross-ward connections through therapists only slightly influenced outbreak dynamics.

Two importantdeterminants of outbreak size are sensitivity of the test and the time to reporting. PCR tests have a high sensitivity (98%) compared to rapid antigen tests (50%–80%). The more rapid time to reporting of antigen tests (ie, instantaneous reporting vs 24-hour delay) partly compensates for their lower sensitivity. This finding is in line with other studies that have examined surveillance testing in a model of a nursing home[10] and in the general population.[11]

With both SARS-CoV-2 variants, rapid antigen tests were less efficient than PCR testing with the same frequency. Less frequent testing resulted in larger outbreaks with frequent spillover events to other wards. In practice, PCR testing is usually restricted to 1 or 2 tests per week due to costs. Antigen testing is less costly and may be applied daily or every 2 days. We found that daily antigen testing or testing every other day was superior to twice-weekly PCR testing in containing an outbreak.

In our model, we observed a strong effect pertaining to SARS-CoV-2 variant. When modeling the omicron variant, we observed frequent spillover events to other wards, unless antigen testing was performed daily (Fig. 6). Therefore, surveillance testing alone is not a safe strategy for a virus with transmission properties like the omicron variant. Additional infection control measures, such as contact tracing with active case finding and rapid reduction of inter-ward connections, need to be implemented as soon as a case is detected.

The extent to which cross-ward activities (staff meetings, shared staff) can be allowed without generating spillover events is commonly disputed withing hospitals. To address this, we modeled 3 different setups, ranging from no connection between wards (separated setup), to weekly staff meetings (restricted setup), and to additionally shared staff between wards (regular setup). The connectivity between wards determined the outbreak size. Higher connectivity led to larger and longer outbreaks; however, the differences between the restricted and regular setups were small when surveillance testing was performed more often than every 3 days. Therefore, a small number of inter-ward connections can be allowed under surveillance conditions.

An outbreak of this size would probably lead to a collapse of the entire system and therefore should be avoided. Other measures such as closing or trying to hire other staff were not considered in this model study.

The study had several limitations. Model settings cannot entirely account for the complexity of the real world, and simplification is necessary regarding, for example, the network structure. Furthermore, we estimated some model parameters, such as the probability of transmission because too few data are available in the literature. Thus, our estimates may have been

https://doi.org/10.1017/ice.2023.94 Published online by Cambridge University Press

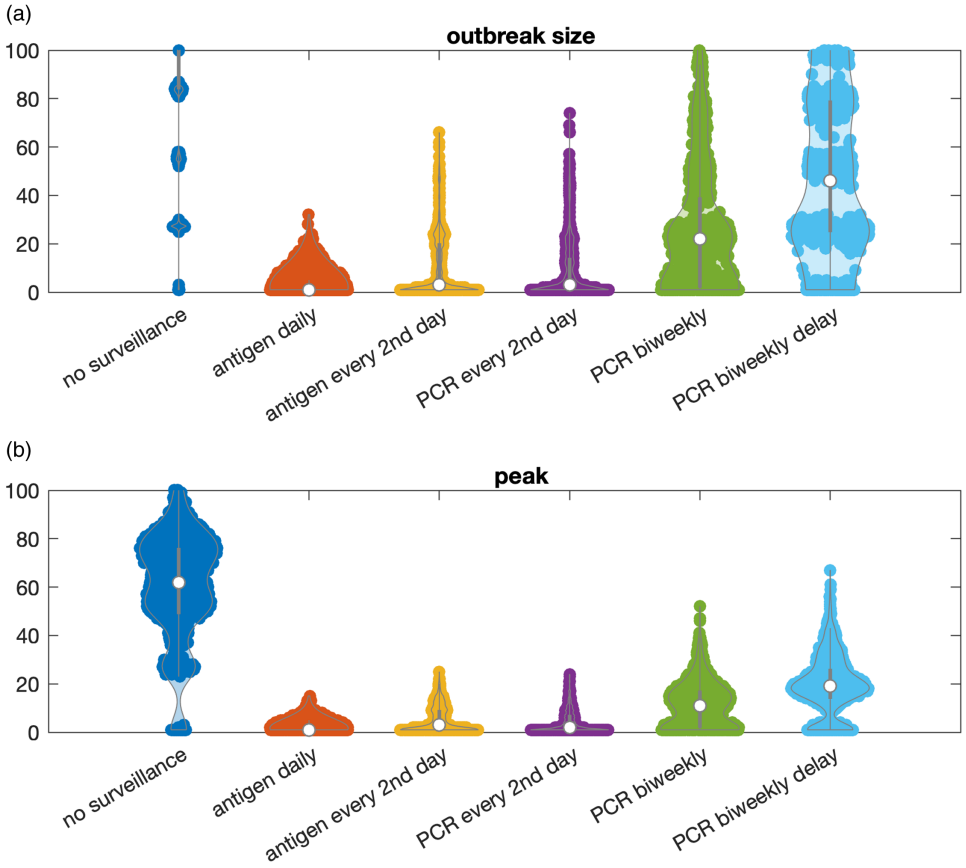

Figure 6. Outbreak size (a) and peak size (b) for no surveillance testing, daily antigen testing, every-second-day antigen testing, every-second-day polymerase chain reaction (PCR) testing, twice-per-week (biweekly) PCR testing with time to report of 1 day, and PCR testing with delayed time-to-report of 2 days. Data shown are for the SARS-CoV-2 omicron variant in the regular setting.

incorrect. We further assumed that the probability of SARS-CoV-2 transmission was the same for each healthcare worker, which did not account for potential superspreader events. Also, we did not explore how masking of staff would have reduced transmission.

On the other hand, the strength of the modeling approach is that we can easily explore the effects of surveillance strategies and virus variants by changing model parameters. However, one should be careful when generalizing the results because network structures vary widely between different settings and can significantly influence outbreak size and duration.

Overall, modeling can generate useful information on outbreak dynamics such as the optimal frequency of surveillance testing and the role of inter-ward connectivity. These data can help to design and select appropriate prevention measures for outbreaks and can help guide local regulations. Surveillance testing can help compensate for increased connectivity via inter-ward activities. However, in addition to surveillance testing, contact tracing and isolation of contacts should be implemented.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/ice.2023.94

Acknowledgments. None.

Financial support. This study was funded by the Bundesministerium für Bildung und Forschung (BMBF) within the project BFAST/NaFoUniMedCovid19 (project no. 01KX2021). The funder did not have any role in conducting the research presented, including study design, programming, data analysis, as well as preparation, submission, and review of the manuscript.

Competing interests. The authors declare no conflicts of interest relevant to the article.

References

1. COVID-19 dashboard. Center for Systems Science and Engineering website. https://coronavirus.jhu.edu/map.html. Published 2022. Accessed June 15, 2022.
2. Crook H, Raza S, Nowell J, Young M, Edison P. Long COVID mechanisms, risk factors, and management. *BMJ* 2021;374:n1648.
3. Hoste L, van Paemel R, Haerynck F. Multisystem inflammatory syndrome in children related to COVID-19: a systematic review. *Eur J Pediatr* 2021;180:2019–2034.
4. Carpenter M, Uebel J, Tomasello M. Being mimicked increases prosocial behavior in 18-month-old infants. *Child Dev* 2013;84:1511–1518.
5. Freiberg A, Horvath K, Hahne TM, *et al.* Beeinflussung der psychosozialen entwicklung von kindern und jugendlichen durch das tragen von gesichtsmasken im öffentlichen raum zur prävention von infektionskrankheiten: ein systematischer review. [Influencing the psychosocial development of children and adolescents by wearing face masks in public spaces for the prevention of infectious diseases: a systematic review.] *Bundesgesundheitsblatt Gesundheitsforschung Gesundheitsschutz* 2021;64:1592–1602.
6. Asen E. *Handbuch der Multifamilientherapie*. Heidelberg: Carl Auer Verlag, 2017.
7. Racine N, McArthur BA, Cooke JE, Eirich R, Zhu J, Madigan S. Global prevalence of depressive and anxiety symptoms in children and adolescents during COVID-19: a meta-analysis. *JAMA Pediatr* 2021;175:1142–1150.
8. Cui X, Zhao Z, Zhang T, *et al.* A systematic review and meta-analysis of children with coronavirus disease 2019 (COVID-19). *J Med Virol* 2021;93:1057–1069.
9. Truong TT, Dien Bard J, Butler-Wu SM. Rapid antigen assays for SARS-CoV-2: promise and peril. *Clin Lab Med* 2022;42:203–222.
10. 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:e2110071.

11. Larremore DB, Wilder B, Lester E, *et al.* Test sensitivity is secondary to frequency and turnaround time for COVID-19 screening. *Sci Adv* 2021;7.
12. Harmon K, St Maurice AM de, Brady AC, *et al.* Surveillance testing for SARS-COV-2 infection in an asymptomatic athlete population: a prospective cohort study with 123,362 tests and 23,463 paired RT-PCR/antigen samples. *BMJ Open Sport Exerc Med* 2021;7:e001137.
13. See I, Paul P, Slayton RB, *et al.* Modeling effectiveness of testing strategies to prevent coronavirus disease 2019 (COVID-19) in nursing homes—United States, 2020. *Clin Infect Dis* 2021;73:e792–e798.
14. Grabowski F, Kochańczyk M, Lipniacki T. The spread of SARS-CoV-2 variant omicron with a doubling time of 2.0–3.3 days can be explained by immune evasion. *Viruses* 2022;14.
15. Patlolla P, Gunupudi V, Mikler AR, Jacob RT. Agent-based simulation tools in computational epidemiology. In: Böhme T, Larios Rosillo VM, Unger H, Unger H, eds. *Innovative Internet Community Systems*. 4th International Workshop, IICS 2004, Guadalajara, Mexico, June 21–23, 2004. Revised Papers. Berlin, Heidelberg: Springer, 2006: 212–223.
16. Jang S, Rhee J-Y, Wi YM, Jung BK. Viral kinetics of SARS-CoV-2 over the preclinical, clinical, and postclinical period. *Int J Infect Dis* 2021;102:561–565.
17. Kim SE, Lee JY, Lee A, *et al.* Viral load kinetics of SARS-CoV-2 infection in saliva in Korean patients: a prospective multicenter comparative study. *J Korean Med Sci* 2020;35:e287.
18. 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.
19. Johansson MA, Quandelacy TM, Kada S, *et al.* SARS-CoV-2 transmission from people without COVID-19 symptoms. *JAMA Netw Open* 2021;4:e2035057.
20. Chen PZ, Bobrovitz N, Premji Z, Koopmans M, Fisman DN, Gu FX. Heterogeneity in transmissibility and shedding SARS-CoV-2 via droplets and aerosols. *Elife* 2021;10.
21. Huber M, Schreiber PW, Scheier T, *et al.* High efficacy of saliva in detecting SARS-CoV-2 by RT-PCR in adults and children. *Microorganisms* 2021;9:642.
22. Fox-Lewis A, Fox-Lewis S, Beaumont J, *et al.* SARS-CoV-2 viral load dynamics and real-time RT-PCR cycle threshold interpretation in symptomatic non-hospitalised individuals in New Zealand: a multicentre cross sectional observational study. *Pathology* 2021;53: 530–535.
23. Al-Rawahi B, Prakash KP, Al-Wahaibi A, *et al.* Epidemiological characteristics of pandemic coronavirus disease (COVID-19) in Oman. *Sultan Qaboos Univ Med J* 2021;21:e195–e202.
24. Scozzari G, Costa C, Migliore E, *et al.* Prevalence, persistence, and factors associated with SARS-CoV-2 IgG seropositivity in a large cohort of healthcare workers in a tertiary care university hospital in northern Italy. *Viruses* 2021;13:1064.
25. Kotsiou OS, Papagiannis D, Fradelos EC, *et al.* Understanding COVID-19 epidemiology and implications for control: the experience from a Greek semi-closed community. *J Clin Med* 2021;10:2765.
26. Jones TC, Biele G, Mühlemann B, *et al.* Estimating infectiousness throughout SARS-CoV-2 infection course. *Science* 2021;373:eabi5273.
27. Viner R, Waddington C, Mytton O, *et al.* Transmission of SARS-CoV-2 by children and young people in households and schools: a meta-analysis of population-based and contact-tracing studies. *J Infect* 2022;84:361–382.
28. Lyngse FP, Mortensen LH, Denwood MJ, *et al.* Household transmission of the SARS-CoV-2 omicron variant in Denmark. *Nat Commun* 2022;13:5573.
29. UK Health Security Agency. SARS-CoV-2 variants of concern and variants under investigation in England. Technical briefing 32. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1042688/RA_Technical_Briefing_32_DRAFT_17_December_2021_2021_12_17.pdf. Published 2021. Accessed June 15, 2022.

https://doi.org/10.1017/ice.2023.94 Published online by Cambridge University Press