Agent-based simulations for optimized prevention of the spread of SARS-CoV-2 in nursing homes

Authors

Jana Lasser[1,2], Johannes Zuber[3], Johannes Sorger[2], Elisabeth Klager[4], Maria Kletečka-Pulker[4,5], Harald Willschke[4], Katrin Stangl[6], Sarah Stadtmann[6], Christian Haslinger[7], Peter Klimek[1,2], Thomas Wochele-Thoma[4,6*]*

Affiliations

(1) Medical University Vienna, Section for Science of Complex Systems; Center for Medical Statistics, Informatics and Intelligent Systems, Spitalgasse 23, 1090 Vienna, Austria
(2) Complexity Science Hub Vienna, Josefstädterstraße 39, 1080, Vienna, Austria
(3) Research Institute of Molecular Pathology, Campus-Vienna-Biocenter 1, 1030 Vienna, Austria
(4) Ludwig Boltzmann Institute for Digital Health and Patient Safety, Spitalgasse 23, BT86, 1090 Vienna, Austria
(5) University Vienna, Institut für Ethik und Recht in der Medizin, Spitalgasse 2-4, 1090 Vienna, Austria
(6) Caritas Erzdiözese Wien, Albrechtskreithgasse 19-21, 1160 Vienna, Austria
(7) Hygienefachkraft-unlimited, Oswaldgasse 14-22/2/11, 1120 Vienna, Austria

* Corresponding authors: Thomas.Wochele-Thoma@caritas-wien.at, peter.klimek@meduniwien.ac.at

Abstract

Due to its high lethality amongst the elderly, nursing homes are in the eye of the COVID-19 storm. Emerging new test procedures, such as antigen or RT-LAMP tests, might enable us to protect nursing home residents by means of preventive screening strategies. Here, we develop a novel agent-based epidemiological model for the spread of SARS-CoV-2 in nursing homes to identify optimal preventive testing strategies to curb this spread. The model is microscopically calibrated to high-resolution data from actual nursing homes in Austria, including the detailed networks of social contacts of their residents and information on past outbreaks. We find that the effectiveness of preventive screenings depends critically on the timespan between test and test result, the detection threshold of the viral load for the test to give a positive result, and the screening frequencies of residents and employees. Under realistic conditions, we find that preventive screening of employees only might be sufficient to control outbreaks in nursing homes (on average, one or less secondary infections per index case), provided that turnover times and detection thresholds of the tests are low enough. For the tests considered in this study, we conclude that same-day turnover PCR and RT-LAMP procedures allow for more effective prevention compared to antigen and PCR tests.

Introduction

Nursing homes and other long-term care facilities are the ground zero of the COVID 19 pandemic (Barnett & Grabowski, 2020). Around the globe, a disproportionate amount of confirmed deaths has been attributed to nursing home residents. For instance, as of July 2020, nursing homes accounted for 37% of the 719 confirmed COVID deaths in Austria (52% of all female, 25% of all male fatalities) (BMSGPK (Hg.), 2020, p.). With 923 confirmed cases in nursing homes during this period of time, this gives a case fatality rate of 28%, in line with reported high case fatality rates in the age group above 80 y (Dowd et al., 2020).

Due to this extreme severity, in most countries stringent non-pharmaceutical interventions have been suggested for nursing homes, such as bans on visitors, individual movement restrictions, and other isolation policies (Ouslander & Grabowski, 2020; Wang et al., 2020). COVID 19, therefore, severely affects the quality of life of all nursing home residents, not just the infected ones (Fallon et al., 2020). With an increasing number of countries experiencing resurgences in infections, and in the absence of antiviral medications and vaccines with proven safety and efficacy amongst the elderly, both the direct (mortality risk) and indirect (reduced quality of life) impacts of COVID 19 are expected to further intensify.

The widespread availability of novel rapid testing procedures, e.g. antigen tests (Dinnes et al., 2020), or tests based on the RT-LAMP procedure (Park et al., 2020), might turn out to be a disruptive innovation to control the spread of COVID in nursing homes. With cheap unit costs (orders of 1USD per test) and durations of less than an hour, such tests enable the design of “testing for mitigation” strategies. The aim of mitigation testing is to use widespread testing within a specific setting to quickly identify and isolate infectious individuals but, in contrast to diagnostic testing, not necessarily infected individuals which don’t have a high enough viral load to infect others.

The design of optimal mitigation testing strategies for a specific facility like a nursing home is challenging due to the large number of mutually interrelated factors that determine the effectiveness of a given strategy (Hatfield et al., 2020). Next to the epidemiological contagion dynamics, the optimal testing strategy also depends on the structure of the contact networks of the employees, residents, and their visitors, as well as the characteristics of the test. Two of these test characteristics are of particular importance for mitigation testing, namely (i) the turnover time (time span between test and availability of test result) and (ii) the detection threshold (viral load necessary for a positive result). For instance, RT-PCR tests, the current gold standard, have a turnover time of one or two days and a detection threshold that is typically much lower than the threshold above which an infected individual becomes infectious. Antigen tests have a turnover of less than an hour but a substantially higher detection threshold than PCR tests. Finally, RT-LAMP

tests combine a same-day-turnover with a low detection threshold. For all these tests, sensitivity and specificity are close to 100% above the corresponding detection thresholds (Aziz et al., 2020; Kellner et al., 2020; Liotti et al., 2020).

Here, we aim to design optimal mitigation testing strategies for nursing homes for different testing technologies by means of agent-based epidemiological modelling (Pastor-Satorras et al., 2015). In particular, we propose a compartmental model that is calibrated with individual-level data from an actual Austrian nursing home. Within this model, individuals are initially in a susceptible state (S). After exposure (E), they turn infectious (I). Depending on the test technology, individuals can be tested as positive either before or after turning infectious. Infected individuals either recover (R) or they are identified by a test and quarantined (X); we refer to these dynamics as the SEIRX model. It is a variant of the recently introduced SIRX model (Maier & Brockmann, 2020) which introduced interventions such as isolation of infected cases to the classic susceptible-infected-recovered epidemiological dynamics. By its explicit use of a detailed contact network, it is similar to a recently introduced model (Thurner et al., 2020).

Contagions occur on a network of social contacts (Wasserman & Faust, 1994) that is derived from the actual living condition in a nursing home (see fig. 1) and fully calibrated using observational outbreak data (see supplementary materials). We consider residents and employees with different types of social interaction such as shared room, lunch table, or common area. Furthermore, we use infection data from four recorded outbreaks to calibrate the epidemiological parameters of the SEIRX dynamics. Mitigation testing strategies are parameterized by test technology and screening frequency. We consider RT-PCR, antigen, and RT-LAMP tests as well as their specific turnover times and detection thresholds. Furthermore, the strategies are determined by the frequencies by which all residents and employees are screened, respectively.

For a given test technology and maximal capacity (number of tests per day), we compute the expected distributions of outbreak sizes, i.e. number of infected residents, for different screening frequencies. In particular, we assume that index cases are introduced either through personnel or through contacts of residents with external people (e.g., visitors). The optimal testing strategy is then identified as the test technology and test frequency for residents and personnel that minimizes the outbreak size for a given number of tests being performed. Our developed simulation framework readily allows for a generalization to nursing homes with other contact networks.

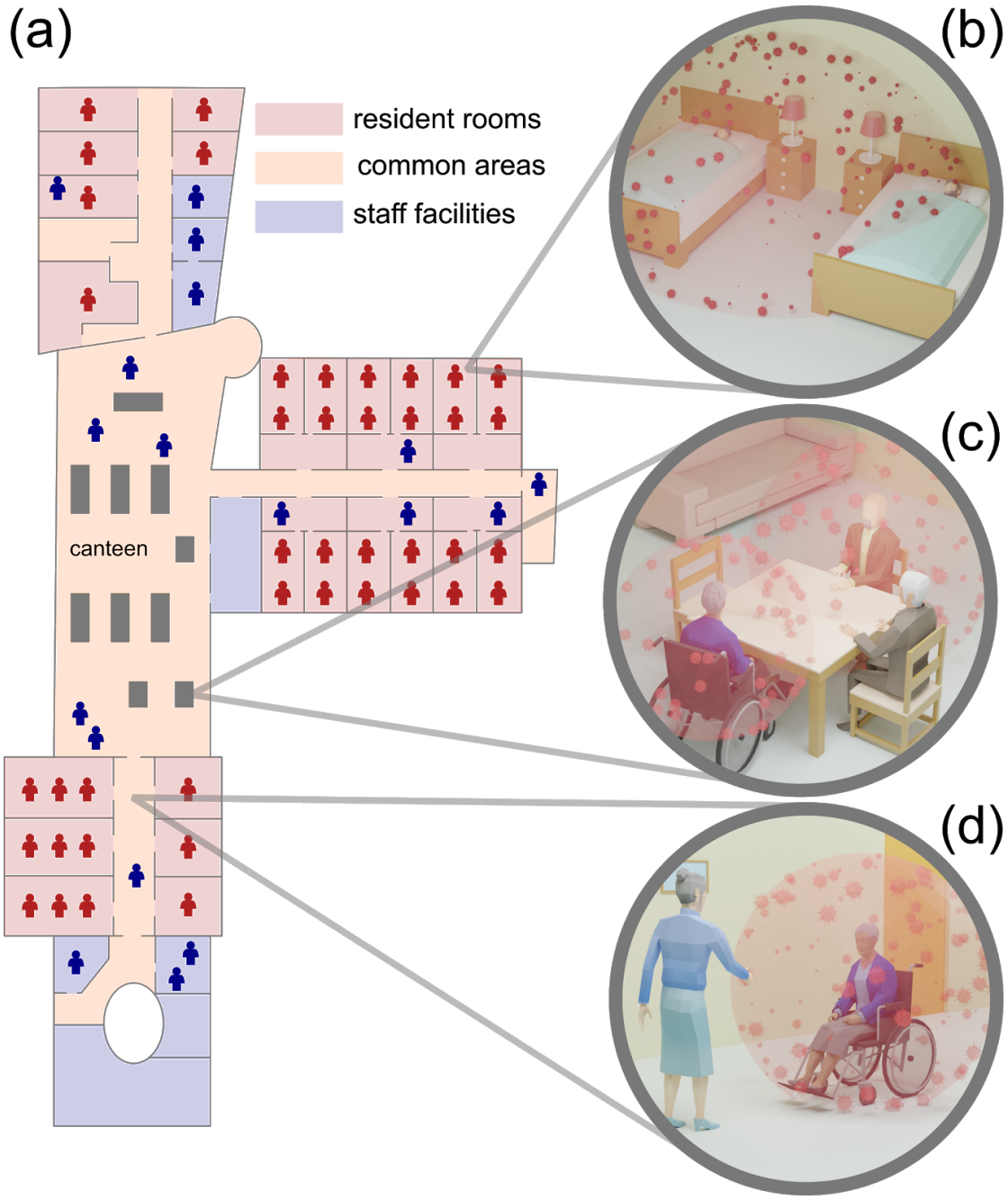

Figure 1: Living conditions in a section of an Austrian nursing home. *(a) Simplified floor plan of the section with resident rooms (red), common areas (orange) and staff facilities (blue). The section houses up to 42 residents (red figures), is staffed by 18 employees (blue figures) and corresponds to the homes described in case studies 2 and 3 (see supplementary material). Contact networks for the simulations were extracted from such floor plans and information about shared tables in the canteen. (b) Rooms: up to two residents share a room and up to two rooms share a bathroom. (c) Shared table: up to six residents share a table during joint meals. (d) Shared common areas: residents living in the same section of the home can move freely within the hallways, canteen and other common areas and regularly meet other residents. Spread of the virus by means of aerosols (Santarpia et al., 2020) is indicated as red clouds.*

Methods

We simulate the infection dynamics using an agent-based model. The model includes two types of agents (residents and employees) that live and work in nursing homes, respectively. Infections are introduced through employees (or inhabitants, or both) with a certain probability to become an index case for secondary infections. Inhabitants have individual networks of social contacts composed of their room neighbors, table neighbors at joint meals and residents that live in the same living area of the nursing home. The contact network defines interactions between residents in one of three ways, in decreasing order of infection transmission risk: Two residents might have social contacts due to a shared room, a shared meal table, or a shared living area. At every step (day) of the simulation, agents interact according to their interaction rules and can transmit the infection. Depending on the viral load over the course of an infection (depicted in fig. 2 (a)), each agent is in one of five states: susceptible (S), exposed (E), infectious (I), recovered (R) or quarantined (X) (depicted in fig. 2 (b)). In addition, agents can stay asymptomatic (I_1) or develop symptoms (I_2). Once an agent has become infected, the agent stays exposed for 4 days, matching the latent time reported for SARS-CoV-2 (Lauer et al., 2020; Linton et al., 2020). After 4 days, agents become infectious and stay infectious for 11 days (Walsh et al., 2020; Wölfel et al., 2020).

The risk of transmission to a contact person is particularly high during the first two days of the infectious phase and then decreases as the infection progresses (He et al., 2020; Walsh et al., 2020). We model this decrease as linear decrease after the first two days until infectiousness vanishes at day 11 after transmission. Approximately 60% of infected agents develop symptoms (Nikolai et al., 2020). The probability to develop symptoms is the same for residents and employees, even though a differentiation might be warranted, given the different demographic structure of the two agent groups (McMichael et al., 2020). If an agent develops a symptomatic course of the disease, symptoms start to appear two days after becoming infectious (6 days after transmission) (He et al., 2020). Infectiousness of symptomatic and asymptomatic cases is chosen to be equal (Lennon et al., 2020), since there are no reports of significant differences in the literature (Nikolai et al., 2020; Walsh et al., 2020). In the model, we split the compartment of infectious agents into two compartments, I_1 and I_2, of asymptomatic and symptomatic cases, respectively.

In our model, each time-step (day) in the simulation is associated with an independent Bernoulli trial for disease transmission between susceptible and infectious agents given a contact (Laskowski & Moghadas, 2014; Mostaço-Guidolin et al., 2011):

$$P_{transmission} = 1 - (1 - \beta(1 - q_1)(1 + q_2)),$$

Where β is the transmission probability per person per time unit, q_1 is a reduction in transmissibility due to the progress of the infection and q_2 is a variable increase in transmissibility due to type of

contact. We calibrate β and q_2 such that the outbreak sizes produced by our model correspond to observed outbreak sizes in nursing homes (see supplementary material). In our model, the basic reproduction number R_0 is 2.61 ±1.33 if an employee is the index case and 4.82 ± 2.01 if a resident is the index case, in the absence of non-pharmaceutical interventions or containment measures (see below) to curb the virus spread. These reproduction numbers are slightly higher than the R_0 previously reported for the spread of SARS-CoV-2 in the literature (Li et al., 2020; Wu et al., 2020), which could be explained by the sometimes crowded living conditions in nursing homes (Brown et al., 2020).

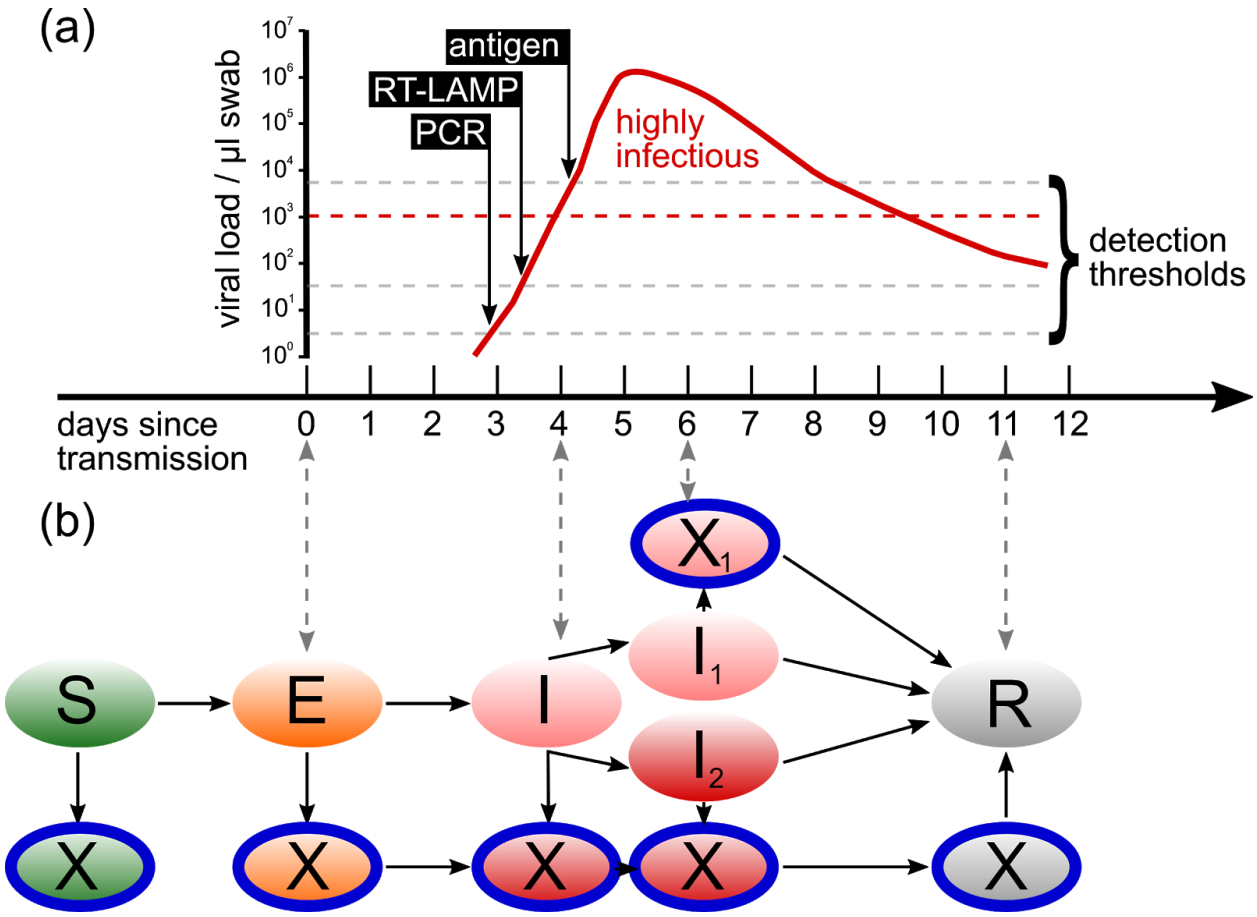

Figure 2: Testability and agent states of the agent-based epidemiological model. *(a) Viral load over time and detection thresholds of PCR, RT-LAMP and antigen tests (Kellner et al., 2020; Larremore et al., 2020; Wölfel et al., 2020): in our model, PCR tests can detect an infection three days after transmission, RT-LAMP tests 4 days after transmission and antigen tests 5 days after transmission. Individuals with > 10³ virus copies per µl swab are considered infectious (Wölfel et al., 2020). (b) Agents in the epidemiological model can be in the states (circles) susceptible (S), exposed (E), infectious (I), infectious without symptoms (I_1), infectious with symptoms (I_2) and recovered (R). Possible state transitions are shown by arrows. In each of these states, agents can also be quarantined (X), preventing them from interacting with other agents. Transitions between states follow the development of the viral load in the host.*

Exposed or infectious agents can be testable – meaning that their virus load is high enough for a given test to detect the infection – depending on the period of time they have already been infected and the test being used (see fig. 1 (a)). Different types of tests also have their specific turnover times (delay between making the test and knowing its result). Tests return positive or negative results, depending on whether the agent was testable at the time of testing. For sake of simplicity, we assume the sensitivity and specificity of all simulated tests to be 100%.

Next to the transmission of the infection, we simulate containment measures (quarantine) and a testing and tracing strategy implemented by the nursing home to curb the spread of the virus. In the baseline scenario, without any preventive screening, only diagnostic testing takes place: Symptomatic cases are immediately quarantined and tested using a PCR test with a one-day turnover time. Once a positive test result is returned, all close contacts of the positive agent are immediately quarantined. Only residents can have close contacts, namely being roommates or table neighbours. Once there is a positive test result, the nursing home launches a "background screen" of its population, testing all its employees and residents with PCR tests with a one-day turnover time, in line with current recommendations (Dumyati et al., 2020).

In addition to the reactive testing and tracing in the baseline scenario, we simulate several scenarios in which the nursing home implements a preventive screening strategy using different testing technologies, independent of reported positive cases. Preventive screens are conducted in the employee group, resident group or both groups in an interval of 2, 3 or 7 days. To simulate the scenarios, a single index case is introduced either via an employee or via a resident and simulations are terminated if no agents are either exposed or infected anymore. We simulate scenarios with all possible combinations of preventive screening frequencies for three types of testing technologies: (1) the PCR test has a turnover time of same-day to two days and detects an infection at around 1 virus copy / μl or four days after transmission (i.e. one day before agents become infectious) and until the infection has subsided (Aziz et al., 2020). (2) the antigen test has same-day turnover and detects an infection two days after an agent has become infectious up until three days before an agent stops being infectious, due to the higher viral load needed for the test to yield a positive result (Liotti et al., 2020). (3) the RT-LAMP test also has same-day turnover and detects an infection for the same period of time an agent is infectious (Kellner et al., 2020).

For each scenario, we compute 10,000 randomly initialised simulation runs in a simulation with 35 residents and 18 employees. The number of residents and their contact network as well as the number of employees correspond to the empirically observed situation in a typical living quarter in Austrian nursing homes (see supplementary material). We report the outbreak size (i.e. number of follow-up cases among residents caused by a single index case over the course of the simulation)

as well as the number of tests per day per person needed to implement the testing strategy in a given scenario.

Results

We simulate epidemic spread in a nursing home in a range of different scenarios: (i) introduction of index cases through either employees or residents, (ii) different testing technologies used for preventive screening and (iii) different intervals for the preventive screens. We report the median outbreak sizes if different testing technologies with different virus detection thresholds are used. We chose to report outbreak size among residents as residents are the most vulnerable group due to the high lethality of COVID-19 in the > 80 y age group (Dowd et al., 2020). In addition to the follow-up cases, we report the number of tests per person and day needed for a given screening policy, where the number of tests is the sum of the tests used for diagnostic testing and preventive screening.

We report our main results as outbreak-heatmaps in fig. 3 for scenarios in which employees (top row) or residents (bottom row) present as index cases. In these heatmaps, rows and columns indicate the preventive screening frequency for residents and employees, respectively. The average outbreak sizes (number of infected residents stemming from a single index case) for a given test strategy (screening frequencies) are colour-coded in the cells. As shown in the outbreak-heatmaps for the different scenarios displayed in fig. 3, median outbreak sizes range between 0 and 6, depending on the scenario. Higher screening frequencies and lower test turnover times always reduce the size of outbreaks. Intuitively, prioritising the agent group that is more likely to introduce index cases in the preventive screening strategy considerably reduces the size of outbreaks. The lowest outbreak sizes of 0 [0; 0] (25%; 75% IQR) are achieved if index cases are predominantly introduced by employees and residents and employees are tested every two days with PCR tests with same-day turnover. The highest outbreak sizes of 8 [5; 12] are recorded if index cases are introduced by residents and no regular preventive screening happens. Nevertheless, it is noteworthy that only reactive diagnostic testing is sufficient to contain outbreak sizes (i.e. the infection is stopped before all residents are infected) in these scenarios.

In a realistic scenario where index cases are introduced by employees, employees are screened every three days (residents are not screened) and PCR tests achieve a realistic maximum turnover time of one day, RT-LAMP tests perform best (outbreak size 0 [0; 2]), followed by PCR tests (0 [0; 8]), while antigen tests perform considerably worse (3 [0; 8]). Nevertheless, if the logistics around PCR tests are optimized such that a one-day turnover can be achieved, PCR tests perform similar than RT-LAMP tests (outbreak size 0 [0; 2]). If employees are screened only once a week, outbreak sizes increase to 1 [0; 7] (LAMP), 3 [0; 8] (PCR) and 5 [0; 9] (antigen). In table 1 we list

mean and median outbreak sizes alongside the 25th and 75th percentile outbreak size range and test rates for each of the three test technologies with same-day turnover, : screening of employees every 2, 3, 7 days or never and screening of residents every 7 days or never.

The base rate of tests needed for reactive diagnostic testing in all scenarios is approximately 0.17 ± 0.1 tests per day per person. Implementation of regular preventive screening of only employees every three days increases this rate to 0.24 ± 0.10 (resident index case) and 0.21 ± 0.16 (employee index case) if, for example, RT-LAMP tests are used. Implementation of regular screening every three days for only residents with RT-LAMP tests increases the rate to 0.32 ± 0.14 (employee index case) and 0.32 ± 0.19 (resident index case). Implementation of screens every two days with RT-LAMP tests for both employees and residents increases the rate to 0.37 ± 0.07 (employee index case) and 0.38 ± 0.07 (resident index case). We note that the increase in test rate cannot be simply calculated using the number of simulated agents and the screening interval, as no preventive screen will take place on days on which diagnostic screens happened and, therefore, the test rate depends on the unfolding of outbreaks.

Next to the detection threshold, another important parameter for regular testing is the test turnover time, i.e. the time it takes for tests to return results. The turnover time determines how quickly contact tracing can start and contacts of infected people are quarantined. In fig. 4, we investigated different turnover times between same-day and two days for PCR tests in the same model setting as described above. These turnover times are realistic for PCR tests, especially in congested testing systems close to overload. For the same scenario described above (employee screening every three days, employee as index case), outbreak sizes for PCR tests with a turnover rate of 2 days increase significantly (4 [0; 9]). Only if both employees and residents are screened every two days, outbreak sizes drop to 1 [0; 6]. PCR tests with same-day turnover are obviously the best option and reduce outbreak sizes to 1 [0; 7], even if only employees are screened once a week.

Staff screen interval [days]	Resident screen interval [days]	Outbreak size mean ± std [infected residents]	Outbreak size median	Outbreak size [25th; 75th] percentile	Test rate mean ± std [tests / day / person]
Antigen tests with same-day turnover					
2	7	5.0 ± 6.2	3	[0; 8]	0.87 ± 0.14
2	never	5.2 ± 6.4	2	[0; 9]	0.24 ± 0.14
3	7	4.7 ± 5.4	3	[0; 8]	0.26 ± 0.13
3	never	4.9 ± 5.5	3	[0; 8]	0.23 ± 0.13

7	7	5.6 ± 5.5	5	[0; 9]	0.23 ± 0.12
7	never	5.8 ± 5.7	5	[0; 9]	0.19 ± 0.12
never	7	6.3 ± 5.5	6	[1; 10]	0.21 ± 0.11
never	never	6.6 ± 5.7	6	[1; 10]	0.17 ± 0.10
LAMP tests with same-day turnover					
2	7	0.7 ± 2.6	0	[0; 0]	0.24 ± 0.14
2	never	0.8 ± 2.9	0	[0; 0]	0.20 ± 0.14
3	7	1.9 ± 3.9	0	[0; 2]	0.24 ± 0.15
3	never	2.2 ± 4.4	0	[0; 2]	0.21 ± 0.16
7	7	3.2 ± 4.4	1	[0; 6]	0.21 ± 0.13
7	never	3.9 ± 5.3	1	[0; 7]	0.18 ± 0.14
never	7	5.4 ± 4.9	5	[1; 8]	0.20 ± 0.11
never	never	6.6 ± 5.7	6	[1; 10]	0.17 ± 0.10
PCR tests with same-day turnover					
2	7	0.7 ± 2.6	0	[0; 0]	0.24 ± 0.14
2	never	0.9 ± 3.0	0	[0; 0]	0.21 ± 0.14
3	7	1.9 ± 3.9	0	[0; 2]	0.24 ± 0.15
3	never	2.2 ± 4.4	0	[0; 2]	0.21 ± 0.16
7	7	3.2 ± 4.4	1	[0; 5]	0.21 ± 0.13
7	never	3.8 ± 5.2	1	[0; 7]	0.18 ± 0.14
never	7	5.5 ± 4.9	5	[1; 8]	0.20 ± 0.11
never	never	6.6 ± 5.7	6	[2; 10]	0.17 ± 0.10

Table 1: *Mean and median outbreak sizes alongside 25th and 75th percentile outbreak ranges and test rate for scenarios, in which employees undergo preventive testing every 2, 3 or 7 days or never, and residents undergo preventive testing every 7 days or never. Preventive testing is performed using either RT-LAMP or antigen tests. Values are calculated from simulations with 10000 randomly initialized runs per scenario.*

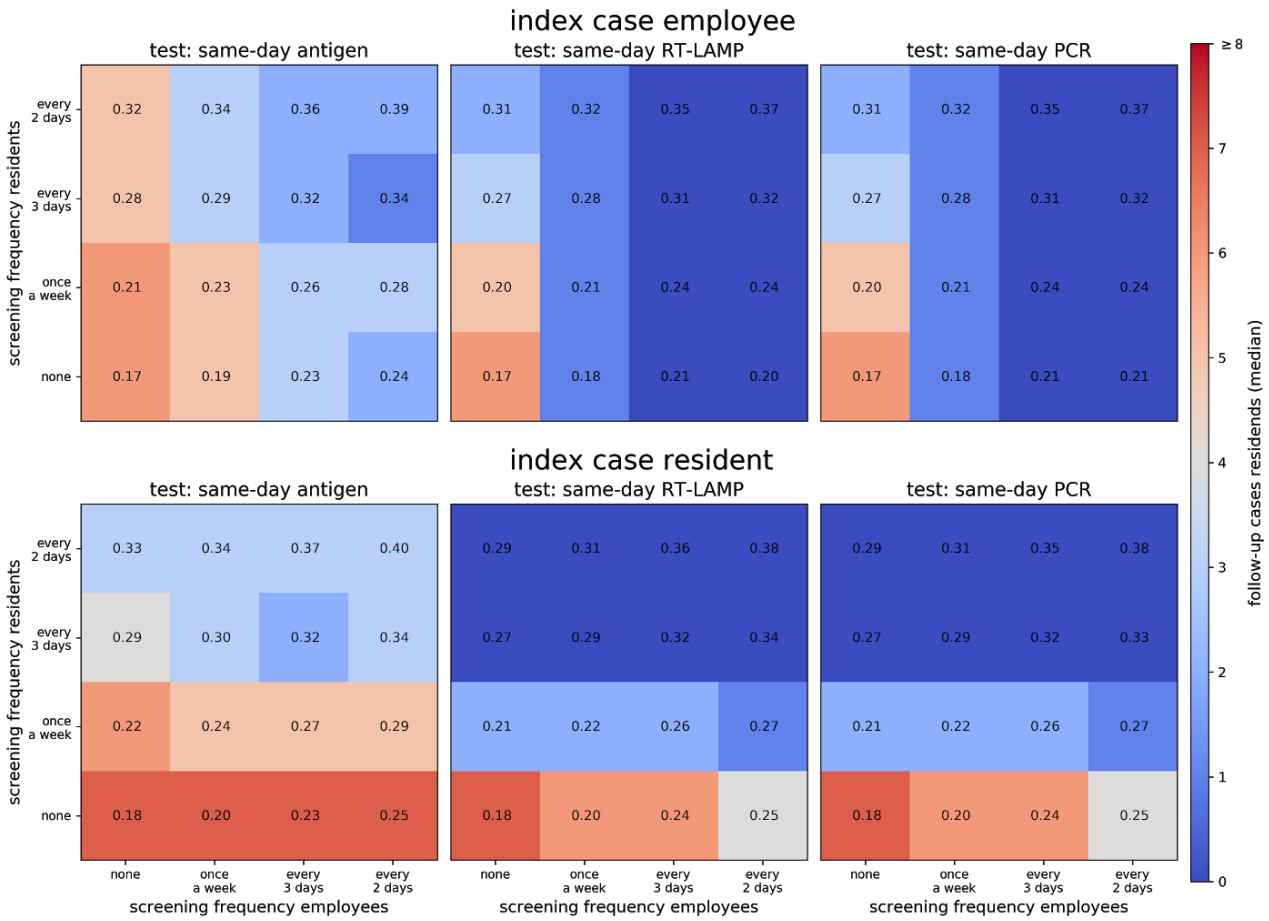

Figure 3: *Outbreak sizes (color in heatmaps) and tests per day per person (numbers on heatmap tiles) for a range of testing scenarios in nursing homes, investigating different testing technologies with their characteristic turnover times. Index cases: in the first row, infections are introduced by personnel, in the second row, by residents (typically after seeing visitors). Testing technology: in the first column, antigen tests with same-day turnover are used, in the middle column, RT-LAMP test with same-day turnover, and in the third column, PCR tests with same-day turnover. Preventive screening frequency: in each heatmap, preventive screening frequency of employees (x-axis) and residents (y-axis) is varied between no screening and one screening every two days. Results represent mean values of 10,000 simulation runs per unique configuration.*

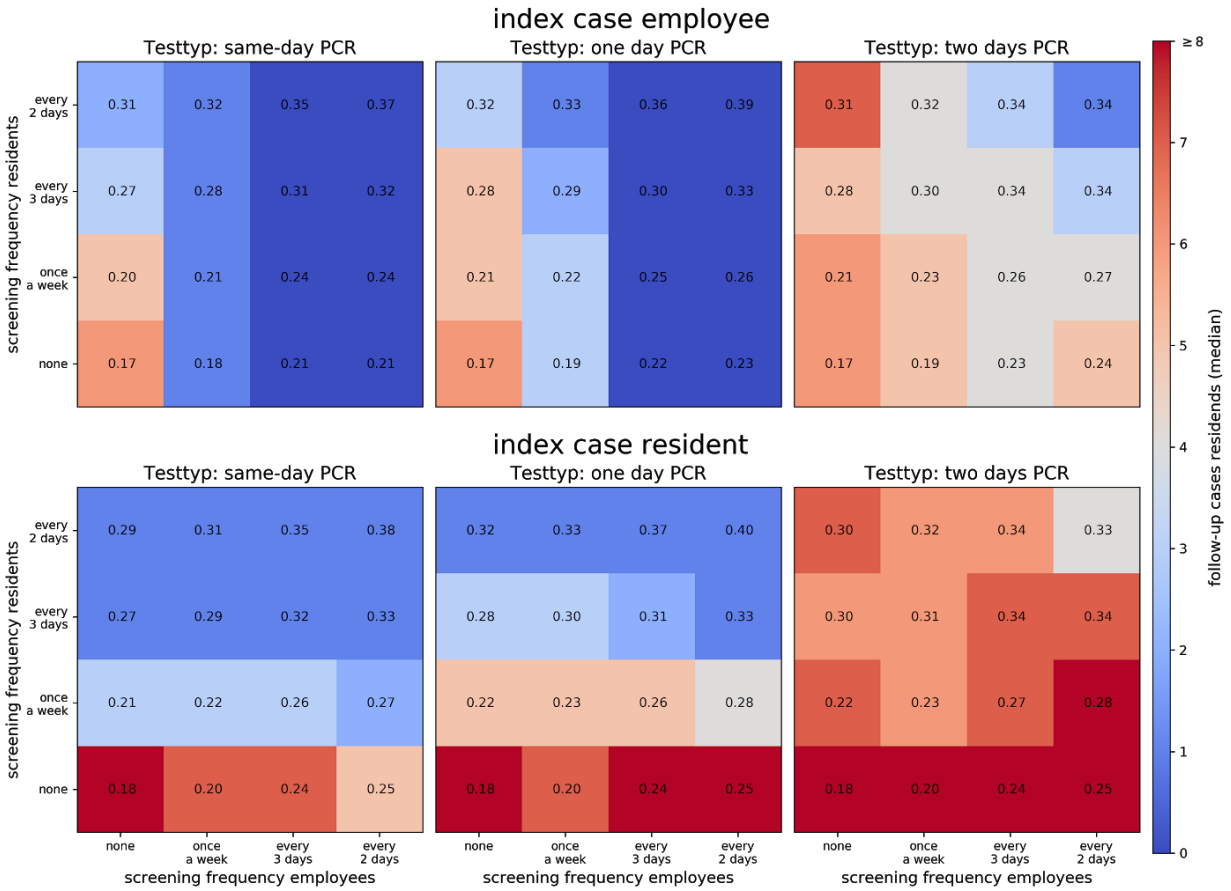

Figure 4: *Outbreak sizes (color in heatmaps) and tests per day per person (numbers on heatmap tiles) for a range of testing scenarios in nursing homes investigating different test turnover times. Index cases: in the first row, infections are introduced by personnel, in the second row, by residents (resembling visitors). Test turnover time: in all scenarios, PCR tests are used. In the first column, tests have same-day turnover, in the middle column, tests have one-day turnover, and in the third column, tests have two-day turnover. Preventive screening frequency: in each heatmap, preventive screening frequency of employees (x-axis) and residents (y-axis) is varied between no screens and one screen every two days. Results represent mean values of 10,000 simulation runs per unique configuration.*

Discussion

In this work, we aimed to design optimal testing strategies for nursing homes by means of a novel agent-based epidemiological model. The model has been calibrated to individual-level contact networks observed in an actual nursing home, and the epidemic dynamics have been calibrated to recorded outbreak events therein. By considering three different testing technologies, we identified testing frequencies for residents and employees that result in the minimal average outbreak size at a given maximal capacity to perform tests.

In brief, our simulations confirm that reactive screening of residents and employees combined with isolation of close contacts of positive cases according to current recommendations for nursing homes (Dumyati et al., 2020) limits outbreak sizes in nursing homes to approximately 6 follow-up cases per index case. In addition, more frequent testing, faster turnover of the test results, and a lower detection threshold for the tests are always beneficial to reduce the average outbreak size. However, the extent to which these individual factors contribute to an outbreak size reduction is non-trivial.

For scenarios in which contacts between residents and visitors or other external people are drastically reduced (or take place with other safety measures like screens, ventilation and face masks), we find that the marginal effectiveness (outbreak size reduction per performed test) of personnel screening strongly outperforms the marginal effectiveness of resident screening. In practical terms, this means that screening only the personnel two or three times per week can have an equal or even higher protective effect than screening all residents once per week. However, in cases where (i) residents frequently have visitors, (ii) these visits take place without other precautionary measures and (iii) the visitors have a high risk to be infected themselves, also screening of residents becomes increasingly important.

All of our results are strongly sensitive to the turnover time between the test being performed and the arrival of the test result. Reducing this timespan from two days to a same-day-turnover might well reduce the average outbreak size from around 4 [0; 9] follow-up cases per index case to 0 [0; 2] cases, in a scenario where personnel is regularly tested every 3 days with PCR tests. In a realistic scenario, where employees are screened every three days and PCR tests achieve a turnover of one day, RT-LAMP tests outperform both PCR tests and antigen tests due to their good detection threshold and fast turnover. Depending on the scenario, antigen tests yield between 0 [0; 1] and 0 [0; 4] false negative tests, which has dramatic consequences, since the false-negative person is not quarantined and is able to freely spread the infection. As RT-LAMP tests are accurate, fast and comparatively cheap, they perform best amongst the testing technologies for regular preventive screening strategies considered in this work. If same-day turnover of PCR tests can be achieved, PCR tests perform similar to RT-LAMP tests but have the

added benefit of allowing for pool-testing, due to their superior detection thresholds (Ben-Ami et al., 2020).

Due to the relatively high detection threshold for antigen tests, these tests can yield negative results, even though an individual is currently infectious. This has important practical consequences in cases where antigen tests are used to exclude the risk of infection and other preventive measures are relaxed. Currently, these tests are purchased by the millions to screen vulnerable population groups and facilitate mass gatherings. There have also been proposals to allow visits to nursing homes only if the visitor tests antigen-negative upon arrival at the facility. Given our results, it is paramount to emphasize that antigen tests provide no certainty that a visitor is indeed not infectious. This means, even if antigen tests turn out to be negative, other precautionary measures like face masks, room ventilation and short visiting times must still be adhered to. Given the pandemic fatigue that many people are experiencing, it is more than questionable whether all visitors will comply with such measures, in particular if they just received confirmation that they are “COVID-negative”.

An issue with preventive screening in nursing homes that deserves further attention is a potential “pull effect” for visitors as testing capacities are strained in many countries and paying for tests out-of-pocket is oftentimes costly. Consider an individual who was potentially exposed to an infected case and considers visiting a related nursing home resident. It might be tempting to make such a visit as there would be the “added benefit” of being tested for COVID. This way, screenings might provide a perverted incentive for drawing individuals with an increased pre-test probability to nursing homes. As our simulations do not account for such externalities, our results concerning antigen tests are based on the assumption that visitors correctly interpret that a negative test result does by no means indicate that other protective measures are not necessary.

There is another practicality that we did not acknowledge in our simulation model, namely how convenient it is to be tested with a given method. PCR and antigen tests require a throat swab that can become quite a nuisance, particularly if employees have to undergo this procedure twice a week. In addition, staff in Austrian nursing homes reports that elderly, often demented residents do not respond well to the often-painful testing. On the other hand, RT-LAMP tests can be performed by gargling a tasteless liquid which might be beneficial for long-term compliance with the testing regimen.

Though most model parameters have been calibrated using individual-level observational data, some simplifying assumptions had to be made. For instance, our model does not account for heterogeneity in the progression through the individual agent states (e.g., differing durations of infectiousness). All contacts of a given type (e.g., table neighbors) are assumed to have the same transmission probability, independent of other environmental factors like ventilation. The viral load

dynamics are approximated in a piece-wise linear way. Finally, one could think of test strategies, in which the time resolution of our model would need to be increased from days to hours to more accurately assess their effectiveness.

In summary, our results indicate that personnel screening twice a week with RT-LAMP or PCR tests can severely reduce outbreak sizes even without a screening of residents, provided that other precautionary measures are taken for social interactions of the residents. Given the same testing strategy, antigen tests provide less protection than RT-LAMP or PCR tests due to their higher detection threshold; a problem that might be exacerbated by negative externalities such as a pull-effect for visitors with an increased pre-test probability and a less convenient testing procedure.

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Ethics

The study was approved by the Institut fuer Ethik und Recht in der Medizin by the University of Vienna under ethics vote EV_2_20052020_KO.

Author contributions

JL programmed the agent based simulation, conducted the numerical experiments, analysed the simulation data, created the visualizations and contributed to writing the original draft of the manuscript.
PK conceptualised the project, supervised the work on the project and contributed to writing the original draft of the manuscript.
TWT conceptualised the project and curated the nursing home outbreak data.
JZ conceptualised the project, contributed to reviewing and editing the manuscript and curated data on test technologies.

JS contributed to reviewing and editing the manuscript and created the illustrations of infection transmissions in nursing homes.
EK conceptualised the project and contributed to reviewing and editing the manuscript.
MKP conceptualised the project, managed ethical aspects of the project and contributed to reviewing and editing the manuscript.
HW contributed to conceptualising the project and reviewing the manuscript.
KS contributed to collecting outbreak data in nursing homes.
SS contributed to collecting outbreak data in nursing homes.
CH contributed to collecting outbreak data in nursing homes.

Competing interests

The Authors declare no competing interests.

Data availability

All data used to calibrate the simulations, simulation results and simulation codes are published at (Lasser, 2020)

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Supplementary information

Model implementation

Design

Our agent based model follows an SEIRX approach, building on the agent based simulation framework mesa (Project Mesa, 2020), written in Python. All code and data is openly available (Lasser, 2020). Agents in the model can be susceptible (S), exposed (E), infectious (asymptomatic I_1, symptomatic I_2), recovered (R) or quarantined (X). The agent states and transitions between states are illustrated in fig. 2 (b). Design choices are based on daily life and practice in Austrian nursing homes. To develop the model, we interviewed people responsible for nursing home management and COVID-19 prevention measures and adapted the design choices accordingly. In addition, we included resident contact networks based on the real living conditions of residents in nursing homes and calibrated the model to reproduce the characteristics of outbreaks of SARS-CoV-2 in Austrian nursing homes (see section “Calibration” below). The model therefore offers the possibility to explore the effectiveness of various testing, tracing and quarantine strategies in the context of nursing homes.

Contacts and transmission

We simulate two types of agents (residents and employees) that live and work in nursing homes. Infections are introduced through employees (or residents, or both) that have a certain probability to become an index case. Residents have an explicitly defined contact network that is defined through their room neighbors, table neighbors at joint meals and residents that live in the same living area of the nursing home. We illustrate an exemplary floor plan from which we extracted the contact network in fig. 1, which resembles the home described in cases 2 and 3 (see section “Case studies” below).

The contact network defines which residents interact with which other residents, and different contact venues modulate infection transmission risk (for example infection risk is drastically increased for roommates). Simulations in this work are run on a contact network corresponding to one housing section of an Austrian nursing home, which housed 35 residents and 18 staff at the time. The contact network extracted from the floor plan in fig. 1 is displayed in fig. A1. In the code and data repository we provide several additional exemplary contact networks, representing different architectures of nursing homes with different numbers of sections and sparse contacts between sections. Contact networks are stored as a networkx graph (Hagberg et al., 2008) with edge attributes for different interaction venues. Employees have no explicitly defined contact network and interact with all residents and all other employees in the same living quarter. In every step (day) of the simulation, agents interact once with other agents according to their interaction

rules and can transmit the infection. In our model, each time-step in the simulation is associated with an independent Bernoulli trial for disease transmission (Laskowski & Moghadas, 2014; Mostaço-Guidolin et al., 2011):

$$P_{transmission} = 1 - (1 - \beta(1 - q_1)(1 + q_2)),$$

Where β is the transmission probability per person per time unit, q_1 is a reduction in transmissibility due to the progress of the infection and q_2 is an increase in transmissibility due to closeness of a contact. We calibrate β and q_2 such that the outbreak sizes produced by our model correspond to observed outbreak sizes in nursing homes (see section “Calibration” and figure A1 below).

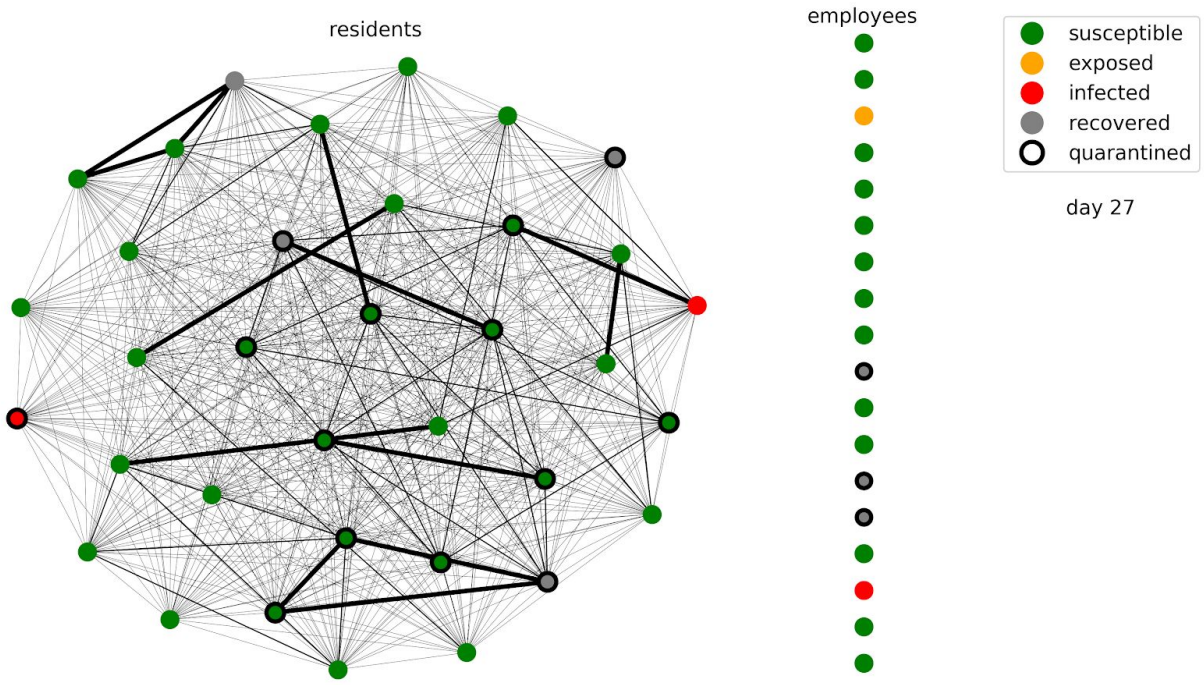

Figure A1: Exemplary contact network of 35 residents (left) with contact intensity indicated by edge thickness. *The 18 employees are displayed to the right. Agent states at the given time-step of the simulation (day 27) is indicated by color: green = susceptible, orange = exposed, red = infected, gray = recovered. A black border corresponds to a quarantined agent.*

Testing

Agents can be testable, depending on the time passed since transmission and the test used. Testability and detection thresholds in relation to viral loads are illustrated in fig. 2 (a). Agents can have a pending test result (tested), which will prevent them from getting tested again before the pending result arrives. This corresponds to the daily practice in diagnostic testing in the nursing homes we model. Tests take a certain amount of time to return results (turnover time), depending on the chosen test technology. Different test technologies can be selected in the simulations. We also implement different test sensitivities and specificities for different test technologies, but use

sensitivities and specificities of 100% for the sake of simplicity in this work. Tests return positive or negative results, depending on whether the agent was testable at the time of testing and on the sensitivity/specificity of the chosen test. Depending on the containment strategy (see below), different tests are used for diagnostic purposes (if an agent shows symptoms or for a background screen after a new positive test is returned), and for preventive screening measures.

Containment strategies

Next to the transmission of the infection, the nursing home implements containment measures (quarantine) and a testing and tracing strategy to curb the spread of the virus among its residents and employees. Symptomatic cases are immediately quarantined and tested, using diagnostic tests. Once a positive test result is returned, all close contacts of the positive agent are immediately quarantined. The definition of "close contact" is also up for specification. In this work, roommates and lunch table neighbours of residents are defined as "close contact", whereas employees have no specific close contacts. If "quarters" is defined as an additional close contact area, all residents residing in the same section of the home as the positive case and all employees working in the same section will also be quarantined. This can be useful if a nursing home with more than one section is modelled.

If there is a positive test result, the nursing home launches a "background screen" of its population, testing all its employees and residents with diagnostic tests. Next to population screening that is triggered by positive test results, the nursing home can implement a preventive screening strategy, where employees and/or residents are tested in set intervals. The tests used for preventive screening can be different from the diagnostic tests used by the home. This is useful since cheaper and faster tests with higher detection thresholds like RT-LAMP or antigen tests might be preferred over PCR tests for preventive screening. The intervals for these screens can be specified and can be chosen differently for the residents and employees. Figure A2 showcases an exemplary timeline of agent states and timepoints of screens for a simulation with 35 residents and 18 employees using one-day turnover PCR tests for diagnostic testing and same-day turnover RT-LAMP tests for preventive screening.

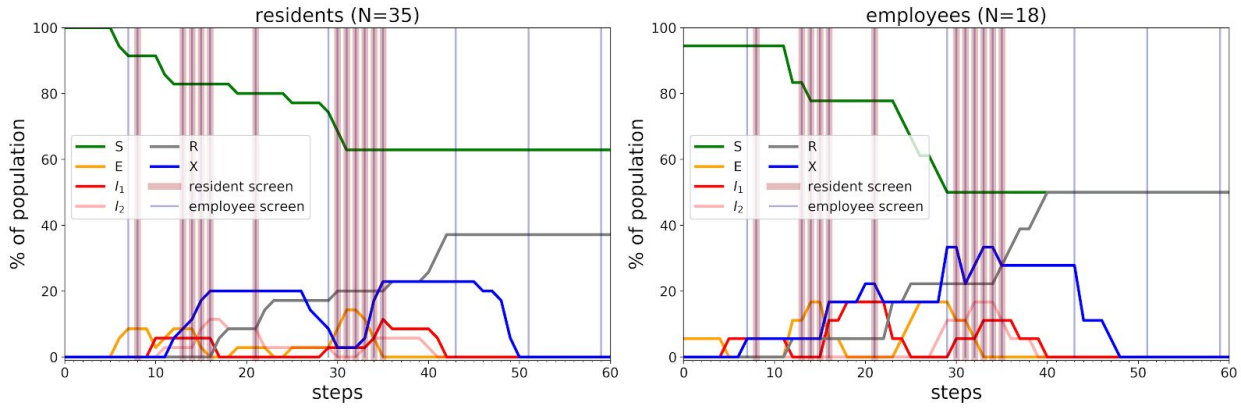

Figure A2 timelines of agent states: *percentage of infected susceptible (S), exposed (E), asymptomatic and symptomatic infected (I_1, I_2), quarantined (X) and recovered (R) residents and employees. Employee and resident screens are indicated as red and blue vertical lines, respectively.*

Calibration

To calibrate the transmission risk between agents in our model, we manually adjusted the transmission risk parameter as well as the modifier for the transmission risk between close resident contacts (shared room, shared table) to best match the infection timelines of the four recorded outbreaks (see description in section “Case studies” below) in a corresponding intervention scenario. The base transmission risk is set at 2.75% for contacts with “intermediate” closeness, and is increased to 8.25% for “close” contacts (roommates) and decreased to 1.375% for residents in the same nursing home section (“far” contacts). Contacts between residents sharing a lunch table and between employees and residents are also considered to be of “intermediate” closeness (transmission risk 2.75% per contact). At the time of the outbreak in the nursing homes, there was no regular screening policy and testing was performed using PCR tests with a two-day turnover. In fig. A3, we show the chronology of recorded outbreaks as well as the number of infected employees and residents over time from simulations. For the simulations we used a corresponding intervention scenario (no screens, two-day turnover PCR tests) in a model that is similar to the nursing home sections described in cases 2 and 3 (35 residents, 18 employees). Since chronological information about outbreaks starts with the day of the first positive test result, we shifted the timelines of our simulations accordingly, such that day 0 corresponds to the first positive test result in the simulation. Means (solid lines) and standard deviations (shaded areas) correspond to values calculated in an ensemble of 1,000 randomly initialised simulation runs.

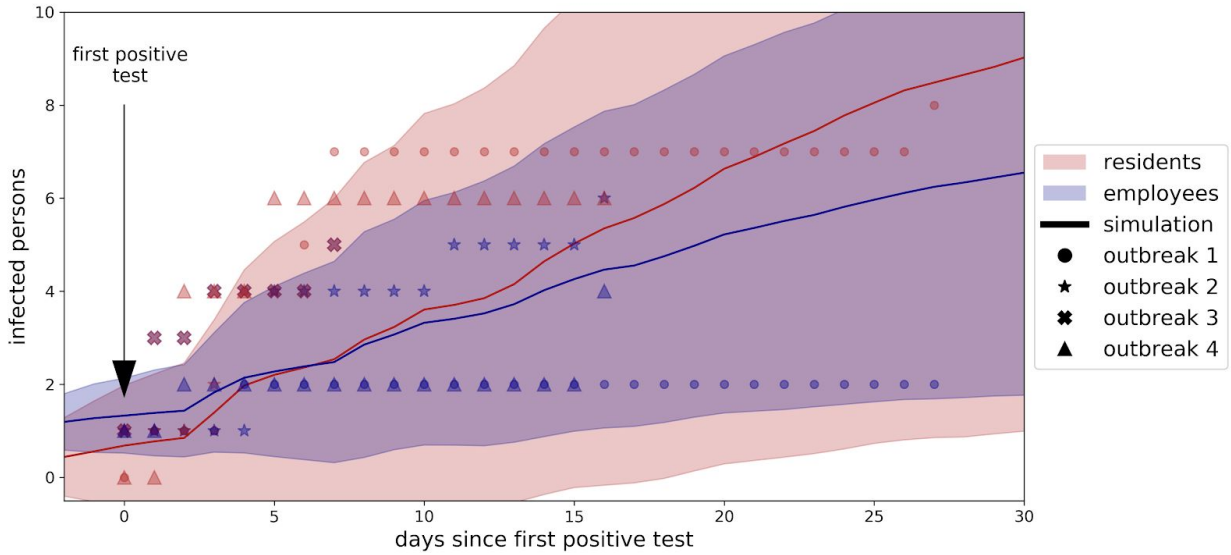

Figure A3*: Infected employees (blue) and residents (red) from the case studies (outbreak 1: circles, outbreak 2: stars, outbreak 3: crosses, outbreak 4: triangles) as well as mean number of infected employees and residents from simulations (1,000 simulation runs). Standard deviation of the number of infected employees and residents from the simulation is indicated as shaded areas.*

Case studies of outbreaks in Austrian nursing homes

In the following we describe the detailed chronology of 4 outbreaks in separate housing sections of two Austrian nursing homes. We chose to treat outbreaks in different sections of the same nursing home as distinct outbreaks. We think this choice is warranted since sections are asked to not share staff as precaution to prevent disease spread and residents do not frequently interact with residents of other sections. In rare cases, staff is shared due to logistic issues such as short-term replacements for staff on sick leave and it is likely that in the cases described here, the virus was introduced to another section of the home this way. Nevertheless, we think that the assumption that contacts between sections are few is justified and introduction of the infection through an employee of another section can be modelled similarly to an infection by an employee that was infected outside the nursing home.

In addition to the four cases described here, we analyzed four other outbreaks in Austrian nursing homes. In each of those cases, an employee was confirmed to be the index case. By now, some Austrian nursing homes have implemented semi-regular staff screening strategies. Through these screens, 10 previously undetected infections in employees could be uncovered and an outbreak in the respective homes prevented. Given this evidence, we think it is warranted to assume that infections in nursing homes are primarily introduced by employees.

Case 1

This outbreak occurred in a section of a nursing home that houses 11 residents. The total number of employees that have regular contact to residents is unknown. Of the 11 residents, 3 and 8 share a table during joint meals, respectively. Residents live in single rooms that share a bathroom with one other resident. The first positive test was recorded on April 3rd 2020. In the ensuing outbreak, 8 out of the 11 residents (73%) and 2 out of an unknown total number of employees were infected. The chronology of the outbreak is described in supplementary table 1.

Day since first positive test	Newly positive employees	Newly positive residents
0	1	0
1	0	1
4	1	3
6	0	1
7	0	2
27	0	1
sum	**2**	**8**

Supplementary table 1*: Chronology of an outbreak in a section of an Austrian nursing home. The index case was most likely introduced by an employee, since the home had implemented a no-visitation policy 21 days prior to the first case. Also three weeks prior to the first positive case, all employees started wearing at least FFP2 masks and gloves when tending to residents. Following the first positive case, all inhabitants were quarantined and confined to their rooms.*

Case 2

This outbreak occurred in a section of a nursing home that housed 35 residents at the time and had approximately 18 employees that have regular contact to residents. Tables were shared in groups of 6 (1 table), 5 (2 tables), 4 (1 table), 3 (2 tables) and 2 (2 tables). In addition there are two single tables and some immobile residents receive their meals in their rooms. Eleven residents live in single-rooms and 24 residents live in double rooms that share a bathroom with another double room. The first positive test was recorded on June 1st 2020. In the ensuing outbreak, 19 out of the 35 residents (54%) and 6 out of 18 employees (33%) were infected. The chronology of the outbreak is described in supplementary table 2.

Day since first positive test	Newly positive employees	Newly positive residents
0	1	1
3	0	1

4	0	9
5	3	0
7	0	1
8	0	1
9	0	1
11	1	1
12	0	1
14	0	3
16	1	0
sum	**6**	**19**

Supplementary table 2: *Chronology of an outbreak in a section of an Austrian nursing home. The first two positive cases were an employee and a resident and it is unclear, whether an employee or a visitor introduced the virus to the facility. Before the first positive case, employees were wearing surgical face masks. After the first positive case, all employees started wearing at least FFP2 masks and gloves when tending to residents and seating arrangements at joint meals were changed to a maximum of two residents per table.*

Case 3

This outbreak occurred in a section of a nursing home similar in number of residents and staff as well as housing conditions as the setting described in case 2. Tables were shared in groups of 4 (5 tables), 3 (1 table) and 2 (2 tables). Some immobile residents receive their meals in their rooms. This section belongs to the same nursing home as the section described in case 2 and the infection was most likely introduced by employees that had contact to residents in both sections. The first positive test was recorded on June 9th 2020. In the ensuing outbreak, 5 out of the 35 residents (14%) and 1 out of 18 employees (6%) were infected. The chronology of the outbreak is described in supplementary table 3.

Day since first positive test	Newly positive employees	Newly positive residents
0	0	1
1	1	2
3	0	1
7	0	1
sum	**1**	**5**

Supplementary table 3*: Chronology of an outbreak in a section of an Austrian nursing home. The first positive case was a resident that was most likely infected by an employee from another*

section of the same nursing home that experienced an outbreak earlier. Before the first positive case, employees were wearing surgical face masks. After the first positive case, all employees started wearing at least FFP2 masks and gloves when tending to residents and seating arrangements at joint meals were changed to a maximum of two residents per table.

Case 4

This outbreak occurred in a section of a nursing home that housed 34 residents at the time. We do not have information about the number of employees that were in regular contact with the residents and about the seating arrangements at joint meals. All residents live in double-rooms. This section belongs to the same nursing home as the section described in case 2 and the infection was most likely introduced by employees that had contact to residents in both sections. The first positive test was recorded on June 10th 2020. In the ensuing outbreak, 6 out of the 34 residents (18%) and 4 employees were infected. The chronology of the outbreak is described in supplementary table 4.

Day since first positive test	Positive employees	Positive residents
0	1	0
2	1	4
5	0	2
16	2	0
sum	**4**	**6**

Supplementary table 4*: Chronology of an outbreak in a section of an Austrian nursing home. The first positive case was an employee that was most likely infected by an employee from another section of the same nursing home that experienced an outbreak earlier. Before the first positive case, employees were wearing surgical face masks. After the first positive case, all employees started wearing at least FFP2 masks and gloves when tending to residents.*