

Preventing COVID-19 spread in closed facilities by regular testing of employees – an efficient intervention in long-term care facilities and prisons

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Abstract

Background: Draconic control measures were introduced to contain the global COVID-19 pandemic, many of which have been controversial, particularly the comprehensive use of diagnostic tests. Regular testing of high-risk individuals (pre-existing conditions, older than 60 years of age) has been suggested by public health authorities. The WHO suggested the use of routine screening of residents, employees, and visitors of long-term care facilities (LTCF) to protect the resident risk group. Similar suggestions have been made by the WHO for other closed facilities including incarceration facilities (e.g., prisons or jails), where in parts of the US, accelerated release of approved inmates is taken as a measure to mitigate COVID-19.

Methods and findings: Here, the simulation model underlying the pandemic preparedness tool CovidSim 1.1 (<http://covidsim.eu/>) is extended to investigate the effect of regularly testing of employees in order to protect immobile resident risk groups in closed facilities. The reduction in the number of infections and deaths within the risk group are investigated as well as the potential economic gain resulting from savings in COVID-19 related treatment costs in comparison to costs resulting from the testing interventions. Our simulations are adjusted to reflect the situation of LTCFs in the Federal Republic of Germany.

The probability is nearly one that COVID-19 spreads into closed facilities due to contact with infected employees even under strict confinement of visitors in a pandemic scenario without targeted protective measures. Regular screening of all employees by PCR tests provides a significant reduction of COVID-19 cases and related deaths in LTCFs. While the frequency of testing (testing rate) and the quality of tests have noticeable effects, the waiting time for obtaining test results (ranging from 12 up to 96 hours) hardly impacts the outcome. The results suggest that testing every two weeks with low-quality tests and a processing time of up to 96 hours yields a strong reduction in the number of cases. Rough estimates suggest a significant economic gain.

Conclusions: The introduction of COVID-19 in closed facilities is unavoidable without thorough screening of persons that can introduce the disease into the facility. These

measures provide an economically meaningful way to protect vulnerable risk groups characterized by an elevated risk of severe infections in closed facilities, in which contact-reducing measures are difficult to implement due to imminent unavoidable close human-to-human contacts.

Introduction

The global COVID-19 pandemic that emerged in Wuhan, China in December 2019 was declared a Public Health Emergency of International Concern by the WHO Director-General in late January 2020 and drastically changed the way of living across the globe [1]. SARS-CoV-2 is an extremely contagious virus affecting the respiratory system [2]. While most infections are asymptomatic and mild, severe infections are life-threatening [3, 4, 5, 6]. If the virus affects the lung it can result in diffuse pneumonia, requiring oxygen supply, hospital, or even ICU treatment [7, 8, 9, 10, 11]. With no effective treatment against the virus, severe episodes can result in death by multiple organ failure [12]. Moreover, severe (and even mild) infections can cause substantial long-term effects, potentially imposing long-term burdens on healthcare systems [13, 14]. From the beginning of the pandemic, older adults and individuals with underlying medical conditions, particularly lung or heart disease, diabetes, obesity, etc. are associated with an increased risk of developing serious complications from SARS-CoV-2 infections [15]. The Centers for Disease Control and Prevention (CDC) identified people aged 65 years and older and people living in a long-term care facility (LTCF) as high-risk groups. Indeed, every second COVID-19 related death in the Federal Republic of Germany occurred within LTCFs [16]. Likewise the rapidly growing elderly population in U.S. prisons [17] is at high risk due to the exceedingly high numbers of infections in such facilities [18].

Draconic control measures were implemented by governments across the globe to prevent the spread of the pandemic, including social distancing (cancellation of mass crowdings and events, enforced physical distance, etc.), curfews, quarantine, and home isolation measures, mandatory use of face masks, accompanied by massive deployment of disinfectants, supply of contact tracking mobile-device applications, and diagnostic tests [19, 20, 21]. Most commonly used are PCR tests that detect the virus in nasopharyngeal swabs, diluted gargle samples, or peripheral blood. As PCR tests amplify virus-specific RNA, they are characterized by very high specificity. The sensitivity of such tests varies across different products on the market. Moreover, PCR tests are easy to perform. Alternatives to quantitative PCR tests are CRISPR-based [22, 23], which are rapidly performed, and have high specificity and sensitivity. Other tests are antibody or antigen based. Such tests are less specific and do not necessarily detect active infections, since antibodies and antigens are present in the blood serum after the infection is cured.

The WHO established guidelines – including regular testing of employees and residents – to protect individuals in LTCFs [24, 25] due to high case fatality rates [26]. Residents of LTCFs constitute a substantial group in high-income countries such as the Federal Republic of Germany. With a population of 82.79 million, the number of people depending on nursing either in LTCFs or at home in Germany increased from 2.5 million in 2011 to 3.41 million in 2017 (over 66% of them being over 90 years old) [27]. The capacity of LTCFs in Germany was 952 367 beds (full stationary capacity: 885 488) in 2017, with 743 120 beds (723 451 full stationary) filled (623 182 beds in 2011, 612 183 being full stationary) [27]. These are sustained by 764 648 employees, 64% of which are care and support personnel [27]. These numbers have an increasing trend: there were additional ambulant care services supported by 829 958 people in need of nursing with 390 322 employees [27].

A similar reasoning applies to incarceration facilities that face challenges in

controlling the spread of COVID-19 [28], and put elderly at particular risk of severe infection [29]. Indeed, jurisdictions in the U.S. have accelerated the release of low-risk offenders [30] as a measure to mitigate COVID-19. An estimated number of 6.4 million individuals were held under the supervision of the U.S. adult correctional system in 2018 (including probation and parole), with an incarcerated population of approximately 2.2 million [31, 32, 33]. There is a notable increase in the age structure of state prisoners, in which the numbers of inmates older than 55, 60, and 65 years of age have quadrupled from 1993 to 2003 [17].

The use of routine screening of residents, employees, and visitors before entering an LTCF by diagnostic tests was mentioned in guidelines by public health authorities [24, 25, 34] and also suggested for incarceration facilities [35]. The impact of such control measures can be studied through the use of mathematical models.

Here, a mathematical model, based on the freely available CovidSIM simulation tool, is adapted to estimate the benefit and economic gain of routine screening for COVID-19 infections of employees in LTCFs and retention facilities by PCR tests. In particular, we study the impact of I. the frequency at which employees are tested, (ii) the processing time to obtain test results, and (iii) the quality of the PCR test in terms of sensitivity. While the model is described verbally in the main text, a concise mathematical description can be found in the S1 Appendix. The model is exemplified by parameters that reflect the situation in the Federal Republic of Germany.

Materials and methods

We study the impact of testing employees in LTCFs or incarceration facilities to protect immobile risk groups from COVID-19 infections using an extended SEIR model, i.e., by a deterministic compartmental model of ordinary differential equations. In particular, the model is an extension of that underlying the pandemic preparedness tool CovidSIM [36]. The flow chart of the model is presented in Fig 1. The model is described verbally with the concise mathematical description found in S1 Appendix. In the description, we focus on LTCFs, although the model equally applies to prisons.

A population of size N is divided into three groups, I. the immobile risk group (R_i), i.e., residents of LTCFs, (ii) the employees (staff) working in LTCFs (S_t), who are in close contact with the risk group, (iii) and the general population (G_e), i.e., the rest of the population.

Each group (G_e , S_t , R_i), is further subdivided into susceptible, infected, recovered, or dead individuals. Infected individuals pass through I. a latency period (not yet infective), (ii) a prodromal period (already partly infective but not yet exhibiting characteristic symptoms), (iii) a fully contagious period (symptoms ranging from non-existent or mild to severe), and (iv) a late infective period (no longer fully contagious). All individuals either recover from COVID-19 and obtain full permanent immunity or die. The model follows the change of the number of individuals, per unit time, being in the susceptible (S), latent (L), prodromal (P), fully contagious (I), and late infective (L) periods, and in the final recovered (R) and dead (D) stages separately for the three population subgroups (G_e , S_t , R_i). Deaths unrelated to COVID-19 are ignored, as we assume a pandemic in a large population in a relatively short time period.

In classical SEIR models, individuals in the latent, prodromal, infected, and late infected classes simply proceed from one stage to the next at a rate directly related to the residence time in each stage. This simplistic flow implicitly assumes that the times individuals spend in the various compartments are exponentially-distributed, and hence have a large variance. In particular, a proportion of individuals progresses too fast, whereas others progress much too slow.

To resolve this, we subdivide the latent, prodromal, fully contagious, and late

infectious periods into several sub-stages, through which individuals pass successively.
This ultimately leads to more realistic durations and hence dynamics.

The characteristics of the population subgroups (Ge, St, Ri) are incorporated within the contact behavior. Namely, the risk group has mainly contacts with other individuals in the risk group and the LTCF employees, whereas their contacts with the general population are limited. The employees (St) have contacts among themselves, with the risk group and the general population. However, the general population has mainly contacts among themselves. Given a contact within or between certain sub-populations, the contact occurs at random. The contact behavior is captured by the contact matrix (see S1 Appendix section “The basic reproduction number and the next generation matrix”).

Susceptible individuals acquire infections through contacts with individuals in the prodromal, the fully contagious, or the late infectious periods at rates β_P , β_I , β_L , respectively, which are identical for each subgroup.

The basic reproduction number R_0 is the average number of infections caused by an average infected individual in a completely susceptible population during the infectious period. In a subdivided population (here Ge, St, Ri), the definition of R_0 is not straightforward and has to be derived from the next-generation matrix [37] (see S1 Appendix section “The basic reproduction number and the next generation matrix”). Importantly, R_0 fluctuates seasonally with a yearly average basic reproduction number of \bar{R}_0 .

First, infected individuals are latent carriers, before they enter the prodromal period, in which they become partly infective. From there, they enter the fully contagious period, at the beginning of which, it is determined whether the infection proceeds as symptomatic or asymptomatic. The likelihood to suffer from a symptomatic episode is elevated in the risk group (Ri).

Covid-19 confirmed individuals are subject to case isolation. Specifically, a fraction of symptomatic individuals will be detected and isolated in quarantine wards (perfect isolation preventing all contacts). If the wards are full, infected individuals are sent into home isolation (imperfect isolation, preventing only a fraction of contacts). Regarding this, there are differences in the subgroups: each symptomatic individual in the risk group will be detected and isolated in quarantine inside the LTCF (perfect isolation), whereas only a fraction of the general population and the LTCF employees will be isolated. Infected individuals further progress to the late infective stage, during which they will stay quarantined as determined during the fully contagious stage. Importantly, LTCF employees will be tested for COVID-19 on a regular basis. We assume that the test is 100% specific, i.e., there are no false-positive test results, reflecting PCR- or CRISPR-based tests [22, 23]. If tested positive, they will be isolated either in quarantine wards or at home, in which case all contacts with the risk group are prevented. Staff can be tested positive during any of the infected stages (latent, prodromal, fully contagious, late infective), however with different sensitivity depending on the characteristic of the COVID-19 test being used, irrespective of symptoms. In particular, there is a possibility (depending on the sensitivity of the COVID-19 test) that employees are isolated already during the latent period before they are infectious. Test results are not obtained instantaneously, but with a time delay. Infected staff can still infect others during this time. The waiting time for the test results depends on the available infrastructure.

Finally, late infected individuals, either recover or die. Only symptomatic infections can cause death. The fraction of lethal infections is higher in the risk group.

All case isolation mechanisms are not initially present, but implemented with a time delay after the initial occurrence of the disease. In addition to case isolation, general contact reducing interventions, e.g., social distancing, curfews, etc. will be sustained for a specific time interval during the beginning of the epidemic. During the time interval

in which case isolation measures are sustained, contacts between the risk group and the general population are reduced, reflecting preventative measure. Furthermore, visitors have to provide a negative test result before entering the LTCF. To obtain conservative estimations the latter intervention is ignored in the simulations.

Fig 1. Model flow chart. The total population is divided into three main groups, the general population (G_e), the employees of the long term care facilities (S_t), and the residents of those facilities (R_i). Infection flows between members of each group as explained in the text.

Implementation of the model

The model following the description in S1 Appendix was implemented in Python 3.8 with a 4th order Runge-Kutta method using the function solve_ivp as part of the library Scipy. Graphical output was created in R [38].

Results

The effect of protecting an immobile risk group (LTCF residents) by regularly PCR-testing LTCF employees, who are the most likely to import the disease into the facility, is studied. Model parameters are adjusted to roughly reflect the situation in the Federal Republic of Germany, one of the countries that has successfully intervened in the COVID-19 epidemic. The model itself is applicable to any industrial nation with an aging population. The aim is to investigate the effects of protecting the risk group and to estimate the demand for PCR tests. Some testing scenarios are not feasible in terms of logistics and available testing capacities, and just serve as a comparison.

The parameters used are listed in Tables 1, and S1 Table-S6 Table. Germany has a population of roughly $N = 83$ million. We assume 700 000 elderly individuals live in LTCFs in which control interventions by PCR testing can be implemented. All employees of LTCFs amount to approximately 760 000. This number however includes employees in the administration and external services, who are not regularly working in these facilities. Hence, a number of 500 000 employees was assumed to work regularly in the LTCFs. The first COVID-19 cases were introduced in the middle of February 2020, corresponding to time $t = 0$. A basic reproduction number of $R_0 = 3.5$ was assumed. When studying the effect of seasonal variation, R_0 was assumed to fluctuate 43% over the year, with an annual average $\bar{R}_0 = 3.5$ and a peak roughly in late December ($t_{R_0\max} = 200$). The average duration of the latent, prodromal, fully contagious and late infective states were assumed to last on average $D_E = 3.7$, $D_P = 1$, $D_I = 7$, $D_L = 7$ days, respectively. In the prodromal and late infective states, individuals were assumed to be half as infective as in the fully contagious state. Individuals in the risk group were more likely to develop severe symptoms ($f_{Sick} = 58\% \text{ vs. } f_{Sick}^{(R_i)} = 70\%$) and had an increased morality ($f_{Dead} = 4.7\% \text{ vs. } f_{Dead}^{(R_i)} = 7\%$). The effect of restricting LTCF access to members of the general population that provide a negative COVID-19 test result upon entry is ignored in the simulations.

In essence, the model without testing interventions is equivalent to the one underlying CovidSim 1.0 or 1.1 [cf. 36, <http://covidsim.eu>]. Hence, we used a combination of general contact reduction and case isolation as proposed in [36].

Clearly, the available capacities of tests, the infrastructure to perform tests, the waiting time for results, and the sensitivity of tests can vary substantially. The impact of these factors is investigated. In any case, the testing intervention has a profound effect on the risk group, while the LTCF staff and, particularly, the general

sub-population are hardly affected (see Fig 2, S1 Fig, S2 Fig). This holds with or
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without seasonal fluctuations in R_0 . Typically, lower sensitivity of tests can be
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compensated by testing more frequently to achieve a given reduction in the number of
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infections within the risk group (see Fig 2B, F, S1 Fig J, S2 Fig J).
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Testing of suspects is central to the interventions as a positive test result triggers a
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series of intervention strategies. The effects of various aspects of the testing intervention
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are explained below.
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Fig 2. Impact of testing intervention: The panels show the number of susceptible (S), infected (I), recovered (R) and
dead (D) individuals at time t , respectively, in the risk group without seasonal variation (A-D) with seasonal variation (E-H)
in R_0 , assuming different tests (colors) and testing frequencies (dashing). The black line in all panels corresponds to the
baseline model without testing. The parameters used are listed in Tables 1, and S1 Table - S6 Table. The dashed grey line in
panels (E-H) corresponds to the value of R_0 (right y-axis).

Testing rate

Assuming a baseline PCR test with a processing time of 48 hours and no seasonality,
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the intervention has a profound effect on the number of infections and deaths in the risk
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group (see Fig 3A-D, S3 Fig E-H). The general sub-population that is hardly affected
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by the testing interventions (see S3 Fig A-D). Hence, the testing has no effect. The
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same holds true for the LTCF staff (see S3 Fig E-H).
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Testing LTCF staff every two weeks (14 days) leads to an almost 10-fold reduction in
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the number of infections and deaths compared to no testing interventions. Increasing
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the testing rate to 1 test per week (7 days), results in a further 25% reduction in
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infections and deaths in the risk group compared with testing every 14 days. The
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reduction in the numbers of infections and deaths for more frequent testing (every two
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days, or daily) is relatively insignificant. Particularly, the differences between daily
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testing and testing every other day is marginal (see Fig 3A-D, S3 Fig I-L).
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In the presence of seasonal fluctuations in R_0 , qualitatively the same picture emerges
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(see Fig 3E-H, S4 Fig). However, the differences between the testing rates are more
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pronounced, particularly between testing every 7 vs. 14 days.
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Fig 3. Impact of testing frequency: The panels show the number of susceptible (S), infected (I), recovered (R) and
dead (D) individuals at time t , respectively, in the risk group without seasonal variation (A-D) with seasonal variation (E-H)
in R_0 , assuming different testing rates (colors). The black line in all panels corresponds to the baseline model without testing
(NT). The parameters used are listed in Tables 1, and S1 Table - S6 Table. The dashed grey line in panels (E-H) corresponds
to the value of R_0 (right y-axis).

Test-processing time

The time needed to process PCR tests, reflecting the testing infrastructure, has only a
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marginal effect, assuming weekly testing in the baseline PCR test and no seasonal
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fluctuations in R_0 (see Fig 4A-D, S5 Fig). Comparing test-processing times of 0.5 - 4
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days (12, 24, 48, 72, 96 hours) does not lead to visible changes in the number of
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infections in the risk group (the other groups are also unaffected, see S5 Fig). The same
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holds true in the presence of seasonal fluctuations in R_0 (see Fig 4E-H, S6 Fig).
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Test sensitivity

The sensitivity of the tests, which varies between the course of the infection, impacts
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the number of infections and deaths in the risk group (see Fig 5A-D, S7 Fig). Weekly
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Fig 4. Test-processing time: The panels show the number of susceptible (S), infected (I), recovered (R) and dead (D) individuals at time t , respectively, in the risk group without seasonal variation (A-D) with seasonal variation (E-H) in R_0 , assuming different processing times in hours (colors). The black line in all panels corresponds to the baseline model without testing. The parameters used are listed in Tables 1, and S1 Table - S6 Table. The dashed grey line in panels (E-H) corresponds to the value of R_0 (right y-axis).

testing with a processing time of 48 hours was assumed in the absence of seasonal fluctuations in R_0 . For simplicity, we compared only tests which had higher or lower sensitivity across all stages of the infection as specified in Table 1. Improving the quality of the test from poor (failure to detect the virus during the latent phase, with a maximum sensitivity of 65%) to intermediate (maximum sensitivity of 75%) yields a 80% reduction in the number of infections in the risk group. A good-quality test (maximum sensitivity 80%), yields another 50% improvement. The effect of increasing sensitivity saturates. Particularly, improving the maximum sensitivity beyond 90% hardly affects the intervention (see Fig 5A-D, S7 Fig I-L).

In the presence of seasonal fluctuations in R_0 the results are more pronounced, especially the improvement from poor to intermediate to good tests (see Fig 5E-H, S8 Fig I-L, cf. Table 1).

Table 1. Test sensitivity.

quality	s_E	s_P	s_I	s_L
poor	0.00	0.10	0.65	0.35
intermediate	0.03	0.30	0.75	0.50
good	0.15	0.60	0.80	0.60
very good	0.25	0.75	0.90	0.65
excellent	0.30	0.80	0.95	0.85

Sensitivity of tests with different quality in the respective stages of the infection.

Fig 5. Test sensitivity: The panels show the number of susceptible (S), infected (I), recovered (R) and dead (D) individuals at time t , respectively, in the risk group without seasonal variation (A-D) with seasonal variation (E-H) in R_0 , assuming different tests (colors). The black line in all panels corresponds to the baseline model without testing. The parameters used are listed in Tables 1, and S1 Table - S6 Table. The dashed grey line in panels (E-H) corresponds to the value of R_0 (right y-axis).

Economic considerations

Moral obligations set aside, the economic gain of the testing interventions can be derived from the results described above. Such considerations must incorporate testing capacities and the available infrastructure.

According to the simulations roughly 258 000 LTCF residents will become symptomatically infected with the virus. Assuming treatment costs of an LTCF resident for flu-like symptoms amounts to 4 000-7 000 Euro, the total cost for all residents are 1.03-1.81 billion Euro. Assuming costs of approximately 40 Euro per PCR test, and intervention with weekly testing (48 times per year and employee) amounts to 960 million Euro. This does not take into account that staff in home isolation does not need to be tested. Testing every two weeks would amount to approximately 480 million Euro.

While this suggests, that the intervention is cost-efficient, the actual gain is likely to be underestimated. Namely, long-term effects of infections and additional costs are not

accounted. Furthermore, costs for testing can presumably be reduced. In particular, the testing intervention results in a 10-fold reduction of the number of infected individuals even under the most conservative setup. Hence, the follow-up costs of infections reduce 10-fold.

Discussion

Elderly citizens and particularly residents of long-term care facilities (LTCF) were identified early as a vulnerable risk group that deserves particular protection, as reflected by the WHO guidelines in March 2020 [24]. Regular testing of LTCF employees and residents for COVID-19 was explicitly mentioned by the John Hopkins University in their Guidance on Protecting Individuals Residing in Long-Term Care Facilities [25]. Furthermore, such recommendations can also be found in the WHO policy brief on preventing and managing COVID-19 across long-term care services from July 2020 [34].

To evaluate the effectiveness of testing interventions to protect resident risk groups in LTCFs we extended the model underlying the pandemic preparedness tool CovidSim [36, <http://covidsim.eu>]. In particular, the deterministic model formulated as systems of differential equations was extended to separate the risk group of LTCF residents and the LTCF employees from the remaining population. Control interventions within the LTCFs affecting the residents and employees roughly reflect the WHO recommendations [cf. 34]. Besides, LTCF employees are regularly tested for COVID-19 and isolated from the resident risk groups if the result is positive. In addition to these control interventions general contact isolation measures (reducing effectively the number of contacts of each individual) and case isolation measures, by quarantine and home isolation were implemented as in CovidSim. Importantly, general contact reduction affects residents and employees in LTCFs differently than the remaining population. Especially, general contact reducing measures between residents of LTCFs are difficult to enforce.

In our investigations, the model was adjusted to reflect the situation in the Federal Republic of Germany. However, the model is not restricted to one particular country but will be applicable to any other industrialised nation with a similar age structure.

The results clearly indicate that regular COVID-19-screening of LTCF employees by testing successfully reduces the number of cases and deaths in the resident risk group. Even with relative conservative assumptions a 10-fold reduction is achieved. Our results indicate that the frequency at which employees are tested has a strong effect. Testing once every 7 to 14 days is sufficient and seems to be a realistic. Although more frequent testing further improves the intervention, the gain is insignificant. Importantly, the waiting time for the return of test results (ranging from 12 to 96 hours) has no noticeable effect. A waiting time of 48-72 hours seems to be realistic when compared with the requirements for international air traveling since summer 2020, requiring passengers to provide proof of a negative COVID-19 test, taken no longer than 72 hours before departure. The quality of the test in terms of sensitivity has a clear impact on the outcome. Here, PCR tests were assumed to be relatively conservative, considering the fact that these tests are constantly improved. Our simple rough estimates of the economic gain of the proposed intervention, comparing the potential costs of COVID-19 treatments with the costs for the testing intervention, is substantial. These estimates are conservative as they do not account for health care costs for long term effects of the infection and capacity shortages in the LTCFs, e.g., due to isolation measures of infected residents. Notably, testing a population of 500 000 LTCF employees every two weeks requires a total of 11.5 million tests per year (assuming 23 tests per person per year), or 221 000 tests per week, which is a realistic number in Germany, having a capacity of approximately 1.4 million tests per week in September 2020 [39].

Notably, similar results can be obtained for serological tests. However, these tests

typically have lower specificity, so that false-positive results can no longer be ignored. Moreover, serological tests will have a lower sensitivity in the early stages of the infection, when the antibody or antigen levels in the patient have not yet reached the detection threshold. Hence, such tests might yield too many false-negative results during the phase when infected individuals are most contagious. Considering the logistics of performing serological tests, only blood draws from finger pricks seem plausible on a large scale deployment as required here, which implies the use of rapid tests. However, COVID-19 rapid tests are cost efficient, with approximate 3-10 Euro per test. Hence, the economic gain would be further amplified due to the cost efficiency.

The proposed intervention considers regular testing only of LTCFs employees (staff) not of residents or the general population upon entry. The reason is that we wanted to study the impact of minimal-invasive control measure. Namely, the risk group is twice as large as the target population being tested. Hence, also testing the risk group would result in the requirement of unrealistically many tests.

It should be noted that general contact reducing measures are modelled in a rather simple way here. Namely, they are sustained only during a certain time interval, disregarding smooth changes in control measures and people's behaviour. The model here can be easily extended to reflect more realistic situations. A contact reduction between the risk group and general population was sustained exceeding the time interval of general contact reduction, and lasted during the whole period in which case isolation measures are in place. The latter can be changed by requiring negative COVID tests of individuals in the general population upon entry into the LTCF. This was ignored in the simulations to obtain conservative predictions.

While the model was parameterized to reflect LTCFs, it also applies to incarceration facilities – particularly, there is a rapidly growing elderly population living in U.S. prisons. The WHO states “Data suggest that without adequate testing, treatment and care in closed facilities, efforts to control COVID-19 in the general population may fail” in May 2020 [40, cf. also [41]]. The structure of prisons makes the execution of distancing measures particularly difficult as contacts between inmates not in isolation are difficult to avoid and the capacity of isolating units is limited. Moreover, wearing personal protective equipment is a challenge for prison guards. The model parameters can easily be adjusted to reflect the situations in incarceration facilities.

Supporting information

S1 Fig. Impact of testing intervention without seasonal fluctuations. The panels show the number of infected (I), susceptible (S), recovered (R) and dead (D) individuals at time t , respectively, for the general sub-population (A-D), the LTCF staff (E-H), and the risk group (I-L) assuming different tests (colors) and testing frequencies (dashing). The black line in all panels corresponds to the baseline model without testing. The parameters used are listed in Tables 1, and S1 Table - S6 Table, no seasonal fluctuations in R_0 are assumed.

S2 Fig. Impact of testing intervention assuming seasonal fluctuations. The panels show the number of infected (I), susceptible (S), recovered (R) and dead (D) individuals at time t , respectively, for the general sub-population (A-D), the LTCF staff (E-H), and the risk group (I-L) assuming different tests (colors) and testing frequencies (dashing). The black line in all panels corresponds to the baseline model without testing. The parameters used are listed in Tables 1, and S1 Table - S6 Table. Seasonal fluctuations in R_0 are shown by the dashed line (right axis).

S3 Fig. Testing rate without seasonal fluctuations. The panels show the number of susceptible (S), infected (I), recovered (R) and dead (D) individuals at time t , respectively, for the general sub-population (A-D), the LTCF staff (E-H), and the risk group (I-L) assuming different testing rates (colors). The black line in all panels corresponds to the baseline model without testing. The parameters used are listed in Tables 1, and S1 Table - S6 Table, no seasonal fluctuations in R_0 are assumed.

S4 Fig. Testing rate assuming seasonal fluctuations. The panels show the number of susceptible (S), infected (I), recovered (R) and dead (D) individuals at time t , respectively, for the general sub-population (A-D), the LTCF staff (E-H), and the risk group (I-L) assuming different testing rates (colors). The black line in all panels corresponds to the baseline model without testing. The parameters used are listed in Tables 1, and S1 Table - S6 Table. Seasonal fluctuations in R_0 are shown by the dashed line (right axis).

S5 Fig. Test-processing time without seasonal fluctuations. The panels show the number of infected (I), susceptible (S), recovered (R) and dead (D) individuals at time t , respectively, for the general sub-population (A-D), the LTCF staff (E-H), and the risk group (I-L) assuming different processing times in hours (colors). The black line in all panels corresponds to the baseline model without testing. The parameters used are listed in Tables 1, and S1 Table - S6 Table, no seasonal fluctuations in R_0 are assumed.

S6 Fig. Test-processing time assuming seasonal fluctuations. The panels show the number of susceptible (S), infected (I), recovered (R) and dead (D) individuals at time t , respectively, for the general sub-population (A-D), the LTCF staff (E-H), and the risk group (I-L) assuming different testing rates (colors). The black line in all panels corresponds to the baseline model without testing. Seasonal fluctuations in R_0 are shown by the dashed line (right axis). The parameters used are listed in Tables 1, and S1 Table - S6 Table. Seasonal fluctuations in R_0 are shown by the dashed line (right axis).

S7 Fig. Test sensitivity without seasonal fluctuations. The panels show the number of susceptible (S), infected (I), recovered (R) and dead (D) individuals at time t , respectively, for the general sub-population (A-D), the LTCF staff (E-H), and the risk group (I-L) assuming various hypothetical PCR tests that vary in their sensitivity in the respective infectious stages testing (colors). The sensitivities of the tests are given in Table 1. The parameters used are listed in Tables S1 Table - S6 Table, no seasonal fluctuations in R_0 are assumed.

S8 Fig. Testing rate assuming seasonal fluctuations. The panels show the number of susceptible (S), infected (I), recovered (R) and dead (D) individuals at time t , respectively, for the general sub-population (A-D), the LTCF staff (E-H), and the risk group (I-L) assuming different tests (colors). Seasonal fluctuations in R_0 are shown by the dashed line (right axis). The black line in all panels corresponds to the baseline model without testing. The parameters used are listed in Tables 1, and S1 Table - S6 Table.

S1 Appendix. Mathematical Description

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