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Explosive COVID-19 outbreak in a German nursing home and the possible role of the air ventilation system

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SUMMARY

Background: Most COVID-19 outbreaks in nursing homes are explained by transmission of SARS-CoV-2 from nurses or visitors.

Methods and results: We describe an outbreak with 64 of the 67 residents identified as COVID-19 cases within two weeks (34 in nursing block 1, 30 in nursing block 2), at least 32 of them had relevant symptoms of COVID-19. Thirteen of the residents' deaths were associated with COVID-19. In addition, 27 of approximately 60 staff members were identified as COVID-19 cases, 23 of them had relevant symptoms. In none of the samples from residents or staff was a mutation of SARS-CoV-2 detected. Quarantine of the residents was already in force at the beginning of the outbreak. A common source among the staff was considered to be unlikely because the two nursing home blocks had no staff rotation and the staff had to wear FFP2 masks during contact with residents. Three months after the outbreak the RNA of SARS-CoV-2 was detected on 14 of 39 sampled indoor surfaces of the air ventilation system with Ct values between 34.9 and 41.9, but only at the air supply in the corridor (11 of 24 samples) and the air overflow in the door between the corridor and the residents' rooms (three of 11 samples) but not at the air exhaust in the residents' bathrooms.

Conclusions: The air ventilation system and an inversion weather situation three days before the first confirmed case may have enhanced viral spread inside the nursing home assuming that a common source with a high viral load had existed at the time of outbreak.

Introduction

The knowledge on possible sources and modes of transmission of SARS-CoV-2 is essential to establish evidence-based concepts of COVID-19 containment. The major mode of transmission remains by droplets, e.g., from one person to another during close face to face contact [1]. The physical distance

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between subjects has thereby a direct impact on the probability of transmission [2,3].

There is an ongoing controversy about the relevance of droplets and aerosol for the transmission of SARS-CoV-2. Coughing is a common symptom of COVID-19 and sheds considerable numbers of virions via droplets and short-range aerosols. That is why individuals with symptomatic infections tend to be more contagious than asymptomatic ones. While singing and talking loudly, highly infectious cases can shed tens to hundreds of SARS-CoV-2 virions per minute via long-range and buoyant aerosols [4].

Some outbreaks of COVID-19 in nursing homes have been described in detail. In many outbreaks, the staff were the source of transmission [5—7], even when fully vaccinated [8], but visitors were also described as a source of transmission [9]. Finally, symptomatic and asymptomatic residents may also spread SARS-CoV-2 resulting in an outbreak [10]. Outbreaks continue to occur in nursing homes even with most of the residents (97.3%) being fully vaccinated [9]. Thus, all types of possible sources and modes of transmission need to be understood to provide the best possible prevention strategy for nursing home residents.

In this report we describe an explosive outbreak of COVID-19 in a nursing home and the possible relevance of the air ventilation system for transmission.

Material and methods

Setting

The nursing home is situated in Cologne, Germany, and has 62 rooms for residents, 53 of them as single rooms and nine as double rooms. The nursing home had 67 residents during the outbreak. Thirty-three of the residents were diagnosed with dementia. The nursing home had two separate residential areas (nursing block 1 with 35 residents and nursing block 2 with 32 residents) including separate nursing teams for each residential area. The floor plans for the nursing blocks are shown in Figures 1 and 2.

Each resident's room had an air exhaust in the bathroom working with negative air pressure. Fresh air was only supplied from the air outlets in the corridors. The air from the corridor could enter the resident's room via an air overflow opening in the door (Figure 3).

COVID-19 case definition

The COVID-19 case definition was based on the national definition provided by the Robert Koch Institute, Germany [11]. Any person was regarded as a COVID-19 case when the following criteria were fulfilled: a person with a laboratory confirmed detection of SARS-CoV-2 by PCR or antigen test irrespective of the type and presence of symptoms.

Outbreak investigation

The Nursing Home Intervention Team was established at the very beginning of the SARS-CoV-2 pandemic at the Cologne Public Health Office to support nursing homes, particularly during outbreak events. It conducted two site visits to the inpatient nursing home during the SARS-CoV-2 outbreak (5th and 9th February 2021) and educated the staff on the correct use of personal protective equipment (11th and 18th February 2021). The case numbers and other findings presented below were collected during these on-site inspections. The residents were tested twice per week (SARS-CoV-2 Rapid Antigen Test, SD Biosensor, South Korea, or NADAL COVID-19 Ag Test, nal von Minden GmbH, Germany) with all results being negative before the outbreak.

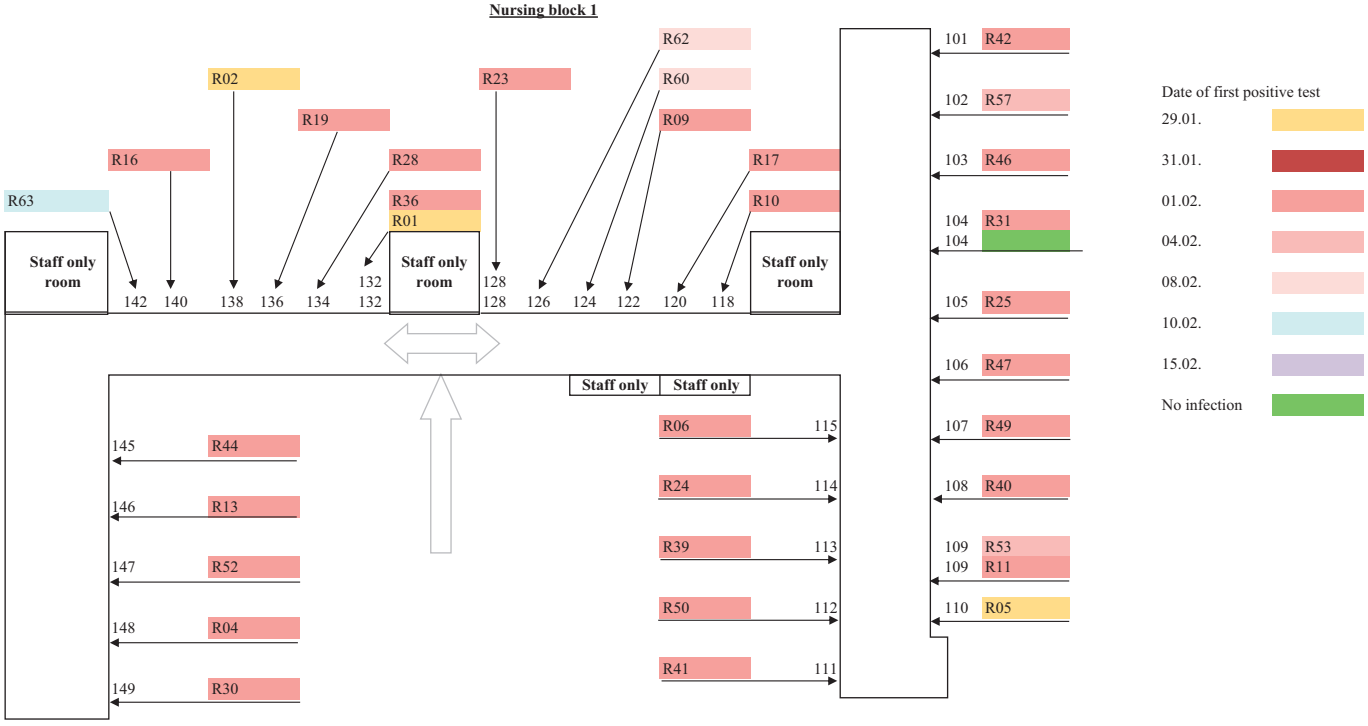

Figure 1. Floor plan of nursing block 1 with rooms 101—149; dates of COVID-19 detection are provided for each resident. R, resident.

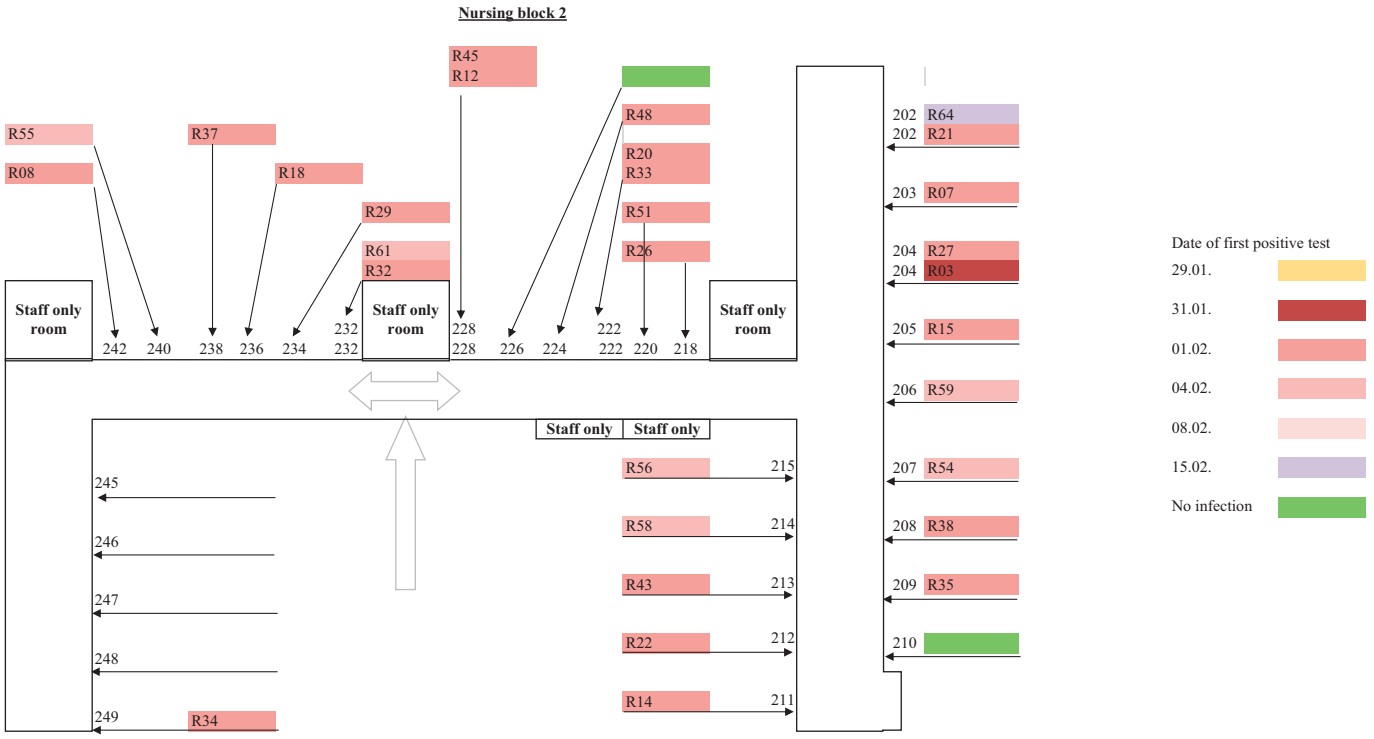

Figure 2. Floor plan of nursing block 2 with rooms 202—249; dates of COVID-19 detection are provided for each resident. R, resident.

Description of the air flow

The existing ventilation and air conditioning system operates entirely with fresh air. The fresh air is fed through an F7 filter. Heat recovery takes place without air exchange between exhaust and supply air.

The fresh air is introduced exclusively into the corridors of the building via supply air openings (Figure 3). From the corridors, the air then flows into the residents' rooms, therapy rooms, group rooms and dining rooms. The fresh air introduced from the supply air openings overflows from the corridors into these rooms. The incoming air is extracted from the residents'

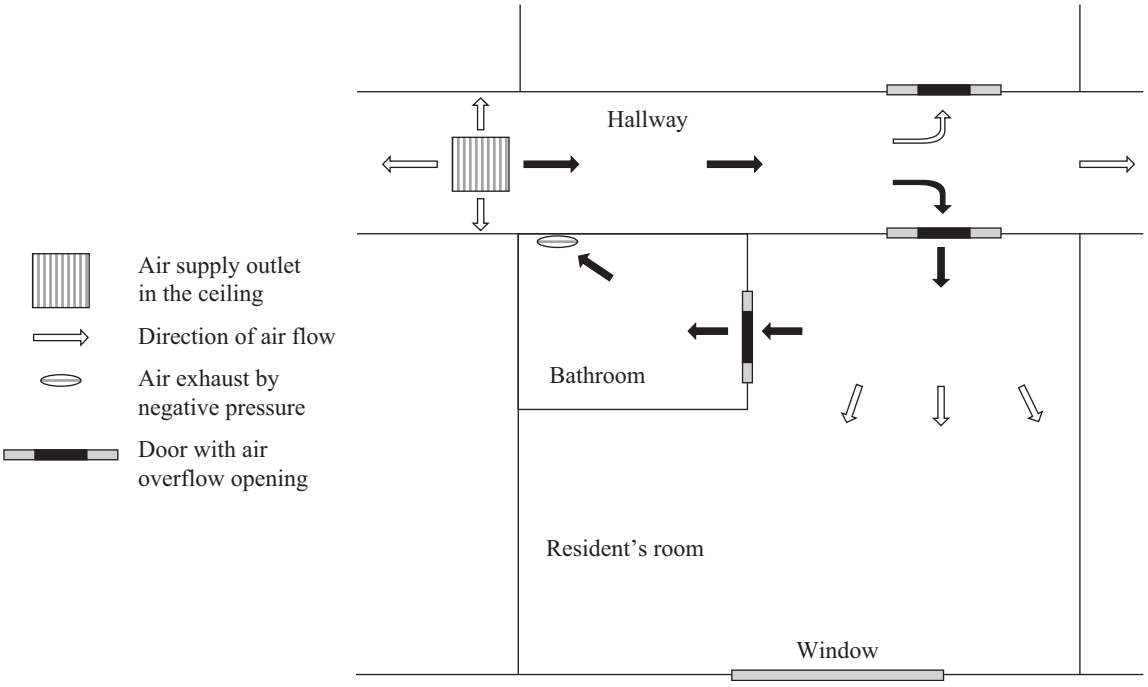

Figure 3. Schematic drawing of the air flow in the residential home; black arrows indicate the shortest possible air circulation from the air supply outlet in the ceiling of the corridor to the air exhaust in the bathroom of the resident's room (negative pressure); white arrows indicate additional directions of air flow.

Figure 4. Exhaust air opening in the tower at the highest point of the roof building of the nursing home as well as the location of the supply air opening (red arrow).

rooms via the sanitary wet rooms (room for toilet, washbasin and showers). The air flow tests indicated that the air from the outlets in the hallway, as indicated in the plans, overflows into the functional rooms and the residents' rooms.

In the dining rooms, the exhaust air is not directed, but exits only through the window opening. The exhaust air for the entire building is discharged centrally via the roof. All of the exhaust air or outgoing air is discharged through a small tower at the highest point on the roof of the building. The supply air is fed into the building through a supply air opening integrated into the gable. This supply air opening is located at a distance of approx. 5—6 m from the central exhaust air opening (Figure 4).

The air conditioning system

The air conditioning system was characterized by an environmental engineer, a specialist in hygiene and a scientist from the Public Health Office during a site inspection on 4th March 2021, taking into account the planning documents and the local conditions. During the visit, the air flows and drifts were measured using flow testing (Dräger Flow Check, Dräger, Lübeck, Germany).

Evaluation of the meteorological situation

For further characterization of the exhaust and supply air flow on the roof of the building, weather data for the period in which the numerous transmissions in the nursing home occurred were determined retrospectively, taking into account the incubation period. For this purpose, the sounding (Stüve diagrams) of the Essen meteorological station, which were downloaded as data from the homepage of the University of Wyoming, and the surface weather analyses from the archives of the German Weather Service (https://cdc.dwd.de/portal/) were considered.

Low wind conditions near the ground and a suppression of vertical transport processes are characteristic for an inversion weather situation. Thus, both horizontal and vertical transport of (trace) substances is strongly restricted, local wind systems (e.g., triggered by small-scale temperature differences) suddenly dominate over the prevailing wind due to large-scale pressure and temperature differences, because the latter is only significant above the inversion [12]. Thermal inversion can be determined, e.g., by radiosondes that measure the temperature gradient with increasing altitude.

Sampling sites of the room air conditioning system

After carrying out the site inspection and characterization of the air conditioning system, a hygienic-microbiological inspection of the supply air and exhaust air openings of the room air conditioning system was carried out on 29th April and 6th May 2021. For this purpose, collective samples were taken from the surfaces. The sterile swabs were moistened with virus transport medium (BD Universal Viral Transport, Becton Dickinson, Sparks, USA) and selected surfaces of the ventilation installations were swabbed. At the supply air openings, the backs of the air outlet and the grids between the air ducts and the air outlet were sampled (Figure 5). In addition, the

Figure 5. Grids between the air ducts and the air outlets.

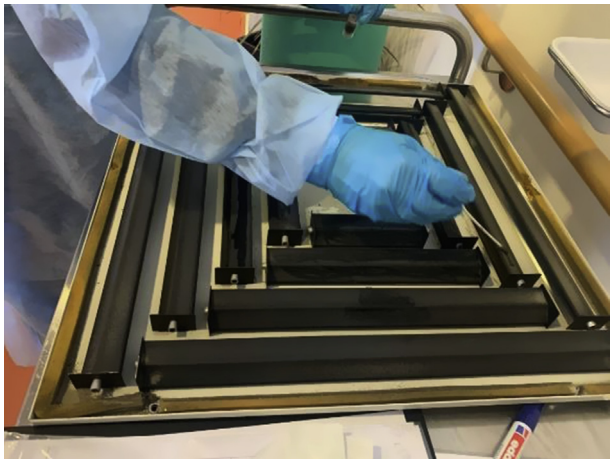

Figure 6. Sampling of the back of the air outlet.

overflow openings between the hallway and the residents' rooms and the exhaust openings in the wet rooms of the residents' rooms were examined (Figure 6). Samples were taken on both floors and on both wings.

PCR tests

Two commercially available and CE-marked SARS-CoV-2 PCR test kits were used. The primary target sequences are located in the E gene (RIDA®GENE SARS-CoV-2 Test, r-Biopharm, Darmstadt, Germany; validated by the manufacturer for surface samples), the secondary target sequences were located in the N1 and N2 gene (Viasure SARS-CoV-2 [N1 + N2] Real Time PCR Detection Kit, CerTest Biotec, Zaragoza, Spain; validated by the manufacturer for samples from human tissue). The entire test procedure was performed according to a local protocol based on the test protocol of the manufacturer which has been described to perform satisfactorily for PCR efficiency (≥96%) [13]. The amplification was performed in a Ridacycler, r-Biopharm, Darmstadt, Germany. A sample was considered to be positive when the cycle threshold (Ct) value for the E gene was ≤35. The Ct value ≤35 was chosen for the E gene because this threshold indicates a viral load of at least 10^5 copies per mL indicating a contamination of possible clinical relevance [14]. In case of a Ct value above 35, an additional PCR test was performed for the detection of the N1 and N2 genes. If the N genes were detected, samples with a Ct value >35 were also considered to be positive. In addition, a point mutation analysis was performed to examine the virus

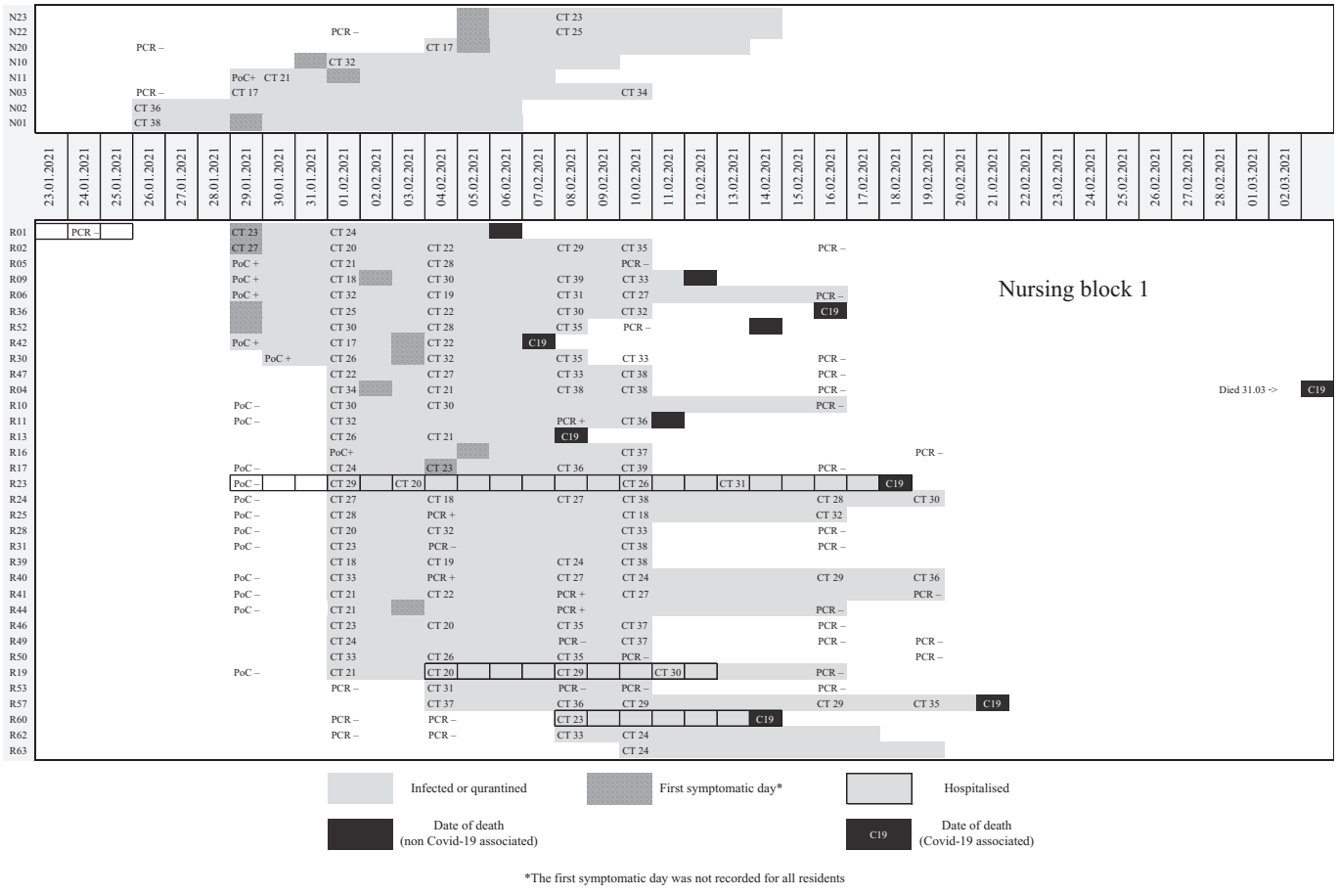

Figure 7. Description of the COVID-19 outbreak among nursing home residents and staff in nursing block 1. CT, PCR cycle threshold; N, staff; PCR −, negative COVID-19 PCR; PoC +, rapid antigen test positive; PoC −, rapid antigen test negative; R, resident.

mutants (RIDA®GENE SARS-CoV-2 Lineage I RUO, r-Biopharm, Darmstadt, Germany).

Results

Description of the outbreak

The nursing home had 67 residents during the outbreak. The first two confirmed cases were nurses from nursing block 1 who were identified on 26th January 2021 (Ct values: 36 and 38). They were initially asymptomatic and therefore continued to work until the positive test results were available on 28th January 2021 (Figure 7). On the same day, another nurse who only worked in an onsite COVID-19 test centre developed symptoms of a respiratory tract infection; she tested positive on 29th January 2021 (Figure 9). On 29th January 2021, four residents and one more member of staff demonstrated symptoms (Figure 9. This staff member had a positive rapid antigen test that was refuted by a negative PCR test the next day. Two of the residents tested positive on the same day by PCR, and additional six residents had positive rapid antigen tests. On 1st February 2021 a total of 38 new cases were found among residents (20 in nursing block 1; 18 in nursing block 2) and seven among members of staff with two of them confirmed by PCR one day later (Figures 7—9).

By 15th February 2021, 64 of the 67 residents were identified as COVID-19 cases (Ct values between 17 and 38; median: 24), with at least 32 of them having relevant symptoms of COVID-19. Of the 17 residents who died during the outbreak, 12 deaths were associated with the COVID-19 infection. An additional resident died two months later, while still recovering from his infection.

During the outbreak 27 of approximately 60 members of staff were identified as COVID-19 cases (Ct values between 17 and 38; median: 23) with 23 of them having relevant symptoms such as fever, headache, severe cough and aching limbs, two of those members tested negative by PCR despite their symptoms. In none of the samples from residents or staff was a mutation of SARS-CoV-2 detected. The staff were last tested by rapid antigen tests on 26th January 2021 with all results being negative apart from the first two cases.

Vaccination status of the residents and staff

The outbreak coincided with the timing of scheduled vaccinations of residents and staff. Only seven of the 64 residents had received a first vaccination with Comirnaty on 4th February 2021, 56 of them were unvaccinated, one resident had an unknown vaccination status. There were also vaccination gaps among staff (23 of the 27 COVID-19 cases were unvaccinated, three were partly vaccinated with Comirnaty with a first injection on 4th February 2021, the vaccination status was unknown in one staff member).

Infection control before the outbreak: staff

Before the outbreak, all employees including kitchen staff, logotherapists, occupational therapists, physiotherapists and

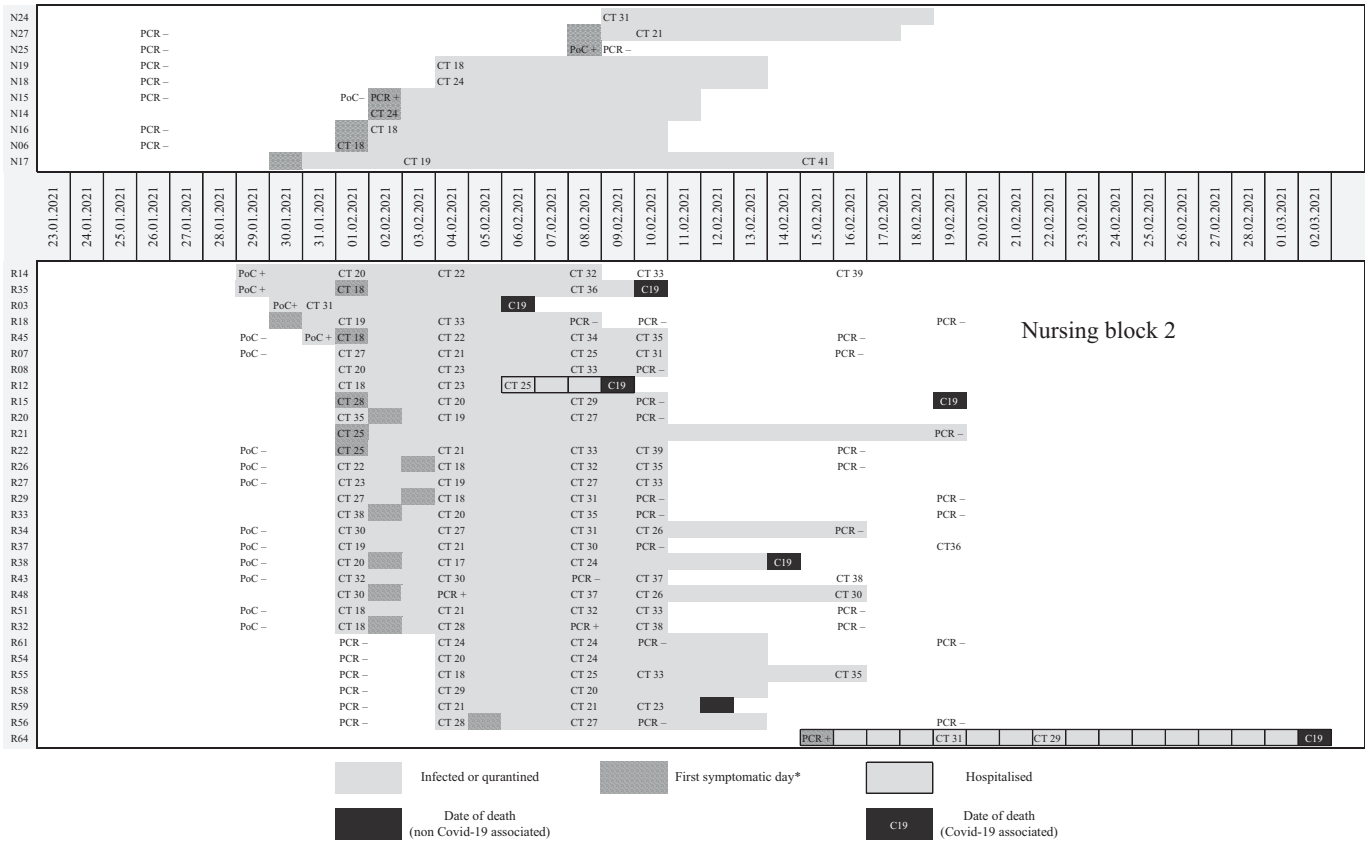

Figure 8. Description of the COVID-19 outbreak among nursing home residents and staff in nursing block 2. CT, PCR cycle threshold; N, staff; PCR −, negative COVID-19 PCR; PoC +, rapid antigen test positive; PoC −, rapid antigen test negative; R, resident.

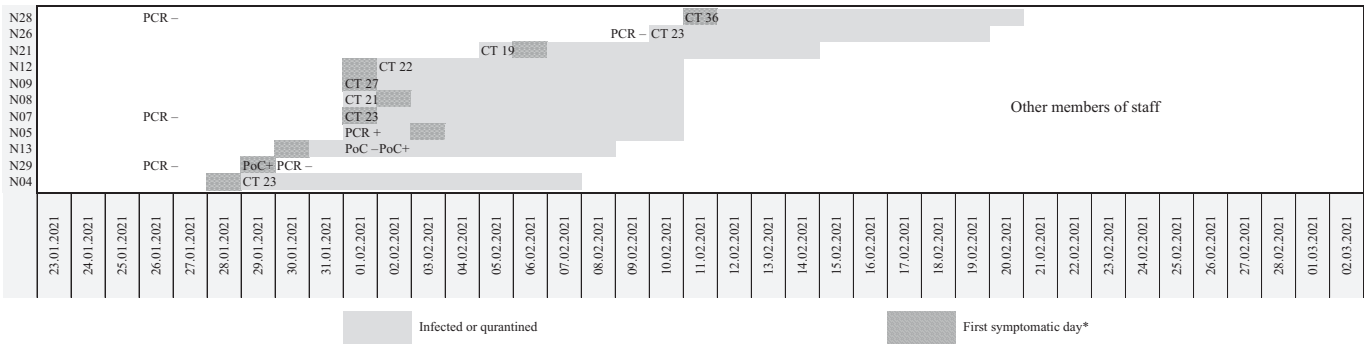

Figure 9. Description of the COVID-19 outbreak among other members of staff; N04, N09 and N21 never entered the nursing blocks 1 or 2; N29, N07, N26 and N28 occasionally entered the corridor of nursing blocks 1 or 2 but never the residents' rooms; N13, N08 and N12 worked in one of the nursing blocks but it was not possible to find out further detail about which of the two; N05 occasionally entered the resident's room but only in the absence of the resident. CT, PCR cycle threshold; N, staff; PCR −, negative COVID-19 PCR; PoC +, rapid antigen test positive; PoC −, rapid antigen test negative.

the employees of the external cleaning company were tested every other week by PCR and also twice a week with the antigen tests described previously.

Employees wore FFP2 masks in the building. Smoking breaks took place outside. Employees were asked to ensure sufficient physical distance from others during the smoking breaks. There was no mixing of the different staff teams from the two residential areas of the house.

Infection control before the outbreak: residents

Residents were tested twice a week with rapid antigen tests as described previously. Residents who had been away from the nursing home were tested after return on days 1, 3 and 6 but only when their absence lasted for more than 6 h.

Upon return from a hospital or for new admissions, PCR testing was performed prior to admission. The residents were isolated for one week and tested with one of the antigen tests described previously on days 1, 3 and 6.

Contacts between residents were reduced to taking meals. There were no group events. Care was taken to maintain sufficient distance in the common areas. The residents themselves mostly did not wear masks in the public areas.

Information about hygiene measures was clearly visible and posted in the relevant languages (German and Russian). In addition, dispensers with alcohol-based hand rub were located in many places and at all entrances, clearly visible and easily accessible.

The following risk points were identified after the inspection and characterization of the indoor air supply system: (1) the close spatial relationship between central exhaust air and central supply air, whereby a short circuit between exhaust and supply air can occur in unfavourable weather conditions; (2) the intended overflow of air from the corridors into the rooms and functional spaces, whereby air possibly contaminated with micro-organisms by people in the corridors can reach all other rooms.

Environmental sampling

On the 29th April 2021 and 6th May 2021, a total of 39 environmental samples were taken from the air ventilation system of the nursing home. SARS-CoV-2 sequences were detected by PCR at several locations in the supply air outlets in the ceiling of the corridor at both testing times. During the first series with 23 samples, eight of them were positive, and six were positive during the second series of 16 samples. Most of the positive samples were from the air duct side components behind the grids of the supply air outlets. On one occasion, SARS-CoV-2 RNA was detected at the overflow opening from the hallway to the resident's room. No SARS-CoV-2 RNA was detected at the resident's room air exhaust vents in the bathrooms. The median Ct values were 40.2 (29th April 2021) and 37.5 (6th May 2021) (Table I).

The environmental testing was performed three months after the outbreak ended such that samples from the residents

Table I
Detection rates of SARS-CoV-2 RNA and corresponding Ct values from indoor samplings of the air conditioning system

Date of sampling	Parameter	Air supply outlet in the ceiling of the corridor	Air supply grid in the ceiling of the corridor	Air exhaust in the bathroom of a resident's room	Air overflow in the door from the corridor to the resident's room	All samples
29th April 2021	Positive samples (*N*)	2 of 6	4 of 8	0 of 4	2 of 5	8 of 23
	Ct values*	39.2**	40.2**	n.a.	41.0**	40.2**
		38.8—39.5***	38.5—40.2***		40.4—41.5***	38.5—41.5***
6th May 2021	Positive samples (*N*)	1 of 3	4 of 7	—	1 of 6	6 of 16
	Ct values*	40.2	36.6**	n.a.	38.7**	37.5**
			34.9—37.7***			34.9—40.2***

*E gene; **median; ***range.

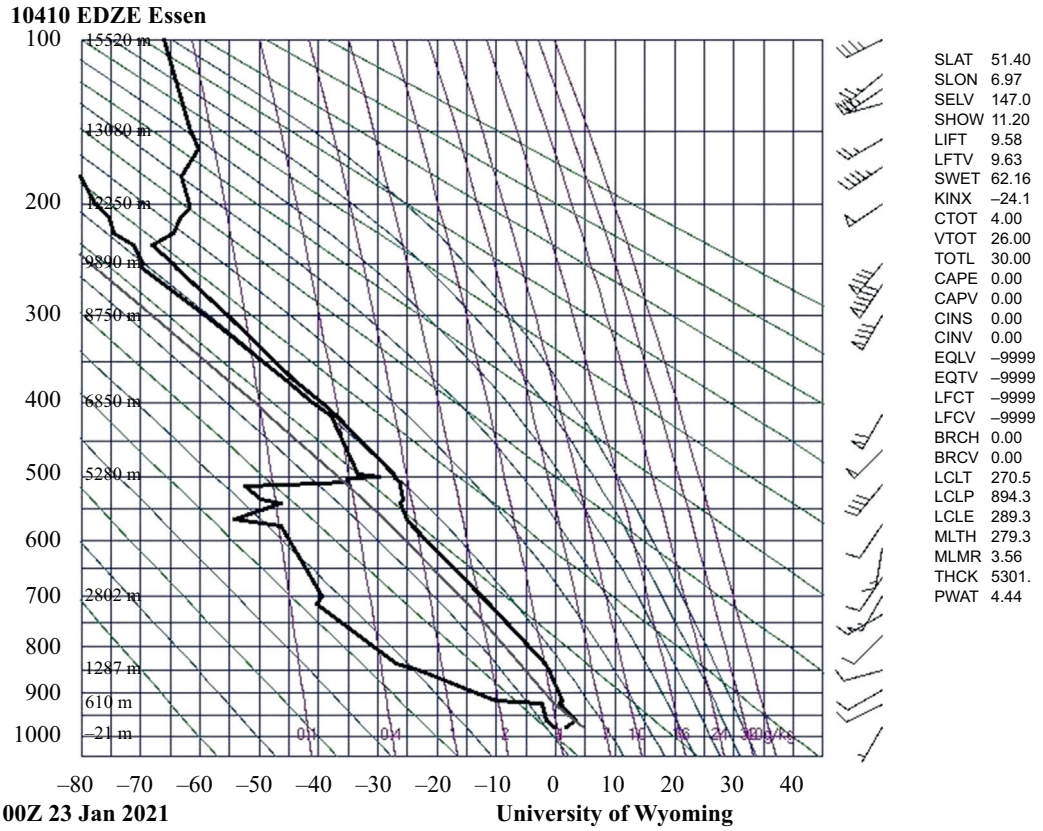

Figure 10. Description of the sounding indices for Essen, Germany, for 23rd January 2021; data obtained from the University of Wyoming, USA (https://www.uwyo.edu/atsc/).

could not be used for gene sequencing testing to match environmental testing.

The environmental samples with a higher viral load (Ct value $\leq$37) were also examined for the marker mutation in the N gene-D3L and the NSP6 106/107/108 del mutation. Both mutations are typical for the B1.1.7 virus variant (alpha variant). The NSP6 106/107/108 deletion alone is also a marker mutation for the B.1.351 (beta) and P.1 (gamma) virus variants. No evidence of mutation was found in the swabs. The environmental samples revealed the wild type, which was still the dominant strain in Germany at the time of the outbreak. This is in agreement with the previous findings in the residents. At the time of the environmental investigation in April and May 2021, approximately 90% of the wild type had already been replaced by VOC alpha (B.1.1.7) [15], thus this finding indicates that the detected RNA originated from the outbreak.

Meteorological situation

Based on the sounding (Stüve diagrams) of the Essen meteorological station, a slight inversion can be recognized retrospectively for 23rd January 2021 from 5000 m altitude (Figure 10). It can be assumed that this stratification was similar in the Cologne area, because such weather conditions generally occur over a larger area [12]. The ground analysis also showed an intermediate high-pressure area for this day, which is consistent with the subsidence inversion evident in the sounding.

On the other days of the period around the outbreak, the stratification was unstable. The pronounced low-pressure area that was located over the North Atlantic before the formation of the intermediate high-pressure area, as well as the occluded front, which formed over Germany afterwards, indicate the strong vertical mixing of the air layers on the days before and after 23rd January 2021.

An additional finding is the direction of wind in the period around the outbreak. Between 20rd January and 10th February 2021 only in the morning of 25th January was the wind coming from north-north-east (https://cdc.dwd.de/portal/ for the station Köln/Bonn with the number 2667). Wind speeds were between 1.4 and 1.6 m/s at this time, which is not very strong. This is exactly the direction from the exhaust air opening in the tower at the highest point of the roof building of the nursing home to the location of the supply air opening allowing particles to move in this direction.

Discussion

The explosive nature of the outbreak suggests a common source affecting most of the residents at the same time. Various explanations are possible.

The first two cases may have been the common source. Both were asymptomatic nurses who were identified as COVID-19 cases two days after swabbing. During the two days they worked as usual in their residential area. One reason that makes this explanation unlikely is that they did not care for all

of the residents who tested positive on 1st February 2021. In addition, they consistently wore an FFP2 mask when in contact with residents. Incorrect use of the mask could at most explain individual infections of the residents they cared for; but the intervention team of the public health department did not identify any errors in the use of the personal protective equipment including the masks among the employees of this facility during the inspections carried out. Finally, their viral load was low on the day of diagnosis suggesting that a wide viral spread is highly unlikely.

It also seems possible that two point sources existed in both residential areas at the same time. But this possible explanation also appears to be unlikely. As of 28th January 2021, all residents no longer participated in common meals in the dining room or other community activities, according to the facility management. At that time, only two staff members were identified as COVID-19 cases, both in nursing block 1. Before the outbreak, common eating took place in three fixed groups in the living area. Infection of all residents within a table group is therefore conceivable, but very unlikely across different table groups and across the two floors. As of 28th January 2021, all residents should have been isolated in their rooms. The last positive test, however, occurred on 15th February 2021, and could therefore hardly be explained by transfers between the residents, but at most by hygiene errors by the staff in caring for the residents. However, by this time at the latest, the employees had taken great care to use FFP2 masks and protective equipment correctly. They could probably also be excluded as possible sources for transmission to the residents although hospital transmission of SARS-CoV-2 has been described from healthcare workers despite wearing N95 masks [16].

Residents who are difficult to isolate and have a high urge to move around are also a frequent cause of transmission in elderly care facilities. For example, because residents with dementia are unable to comply with isolation measures and leave their rooms, they can infect other residents. However, outbreaks caused by residents with dementia and walking tendencies are usually confined to the closer environment or living area of the respective resident. In this case, however, the infection event abruptly spread to both living areas and all parts of the building. Therefore, it is unlikely that transmission by demented residents who could not be isolated led to this outbreak. Furthermore, the intervention team of the public health department could not detect any non-compliance with the isolation measures during any inspection of the facility.

Based on the other observations and investigations made on site, we assume that SARS-CoV-2 could have been transmitted via the ventilation and air-conditioning system, resulting in this explosive outbreak. It would still require a common source spreading enough viral particles to finally reach the infectious dose of approximately 1000 viral particles in most residents and staff in a short time [17]. Such a source was not identified. But various aspects support our hypothesis. One factor is the proximity between the exhaust air opening and the supply air opening which may be a disadvantage during unfavourable weather situations such as inversion atmospheric conditions which were present at the beginning of the outbreak. Another factor is the type of filter used for the supply air. F7 filters (old name) were used which have no viral filtration capacity. A third factor is the consistent repeated detection of SARS-CoV-2 RNA by PCR on supply air grids as an indication that SARS-CoV-2 could have been carried to the supply air grids via the supply air. A fourth factor is air supply to the residents' rooms which came exclusively via the corridors. The exhaust air was removed via the sanitary rooms of the residents' rooms into a central exhaust air duct opening next to the roof tower resulting in an insufficient distance between exhaust air and supply air. Finally, a similar outbreak has been described previously in a residential home with SARS-CoV-1 suggesting that aerosol spread of coronavirus is possible from a common source [18].

In unfavourable weather conditions, it cannot be ruled out that short-circuit flows occur between the exhaust air opening and the supply air opening. Unfavourable weather conditions can be, for example, inversion weather conditions which, in the case of the building under consideration, can lead to the exhaust air not being discharged upwards but being sucked directly back into the supply air opening. Another possibility of a short circuit between the exhaust air and supply air on the roof would be a north-north-east wind situation before the outbreak as described for 25th January 2021. With this wind direction, the air from the exhaust air opening could move directly towards the air supply opening, whereby turbulence in the leeward area could result in exhaust air components getting back into the supply air.

Particles containing micro-organisms, which may be present in the contaminated air sucked back in, are not retained by the F7 filters present in the system as intended. German guidelines, such as DIN EN 167983 and DIN 1946 Part 2, explicitly point out that short circuits between exhaust air and sucked-in supply air must be avoided by maintaining a sufficient distance or by taking suitable technical or structural measures.

A major limitation of our hypothesis is that the RNA results from the air ventilation system were obtained three months after the outbreak. The RNA of SARS-CoV-2, however, has been described to be highly stable when dried on surfaces, with only one log reduction in recovery over three weeks [19]. Another limitation is the lack of viral sequencing to link the environmental and patients' samples, though this is partly compensated for by the three-month retrospective environmental sampling, aided by the subsequent change in circulating SARS-CoV-2 variant. Importantly, a similar outbreak has been described in a Dutch nursing home which was explained by aerosol transmission due to inadequate ventilation [20].

At the same time, it would have been necessary for the source to spread a sufficient amount of infectious virus which was initially in the exhaust air (some droplets may be lost already), for it to enter the exhaust air duct (some droplets may be lost by gravity), to move outside to the supply air opening (dilution by mixing with air is likely), to pass the filter and to finally reach most residents in an infectious dose of at least 1000 viral particles. It has been described that a few super-emitters may produce high amounts of infectious aerosol [21]. This may have been the case in this outbreak. A large fraction of speech aerosol that is intermediate-sized is of concern because it remains suspended in air for minutes and can be transported over considerable distances by convective air currents. The abundance of this speech-generated aerosol, combined with its high viral load in pre- and asymptomatic individuals, implicates airborne transmission of SARS-CoV-2 through speech as the primary contributor to its rapid spread [22].

In conclusion, under certain conditions an airborne transmission of SARS-CoV-2 seems possible, especially when the

transition between droplet and airborne transmission is confluent. That is why it seems plausible to check the ventilation and air conditioning systems in community facilities. Ventilating by open windows may be an alternative when the outside temperature is not too low.

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Conflict of interest statement
All authors declare that they have no conflicts of interest with relevance to the content of this article.

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