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Probable Evidence of Aerosol Transmission of SARS-COV-2 in a COVID-19 Outbreak of a High-Rise Building

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ABSTRACT: Although it is well established that severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) can be transmitted through aerosols, the mode of long-range aerosol transmission in high-rise buildings remains unclear. In this study, we analyzed an outbreak of coronavirus disease 2019 (COVID-19) that occurred in a high-rise building in China. Our objective was to investigate the plausibility of aerosol transmission of SARS-CoV-2 by testing relevant environmental variables and measuring the dispersion of a tracer gas in the drainage system of the building. The outbreak involved 7 infected families, of which 6 were from vertically aligned flats on different floors. Environmenìtal data revealed that 3 families' bathrooms were contaminated by SARS-CoV-2. In our tracer experiment, we injected tracer gas (CO_2) into the dry floor drains and into water-filled toilets in the index case' s bathroom. Our findings showed that the gas could travel through vertical pipes by the dry floor drains, but not through the water of the toilets. This indicates that dry floor drains might facilitate the transmission of viral aerosols through the sewage system. On the basis of circumstantial evidence, long-range aerosol transmission may have contributed to the community outbreak of COVID-19 in this high-rise building. The vertical transmission of diseases through aerosols in high-rise buildings demands urgent attention.

KEYWORDS: SARS-CoV-2, COVID-19, aerosol transmission, mechanism, next-generation sequencing (NGS)

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Introduction

Coronavirus disease 2019 (COVID-19) has threatened human life and the world economy. As of June 14 2023, the COVID-19 pandemic had infected over 767 million people in more than 200 countries and regions, with a death toll exceeding 6.9 million.[1] SARS-CoV-2 primarily spreads through airborne transmission, which is mainly characterized by droplets and aerosols.[2,3] Long-range aerosol transmission, which was overlooked in the early months of the pandemic,[4] has been recognized as an important route of transmission.[5-8] In many densely populated cities worldwide, high-rise buildings are a common form of residential accommodation. However, they pose a significant risk for COVID-19 transmission, potentially due to low mask-wearing rates in residences and workplaces, inadequate ventilation in bathrooms, and close proximity with family members or colleagues. The 2003 outbreak of SARS-CoV in Amoy Gardens demonstrated the potential for aerosol transmission to infect more than 300 residents.[9,10] In the current COVID-19 pandemic, reports have emerged of vertical transmission in high-rise buildings possibly caused by long-range aerosol transmission of SARS-CoV-2 in some densely populated cities.[11-14] However, there is a lack of research on the patterns and factors influencing long-range aerosol transmission of SARS-CoV-2 in high-rise buildings.

In November 2021, there were several COVID-19 outbreaks caused by the Delta variant in China, which were quickly brought under control within 2 to 3 weeks. On November 2, a 23-year-old male was diagnosed with COVID-19 in Chengdu, ending the city's 3-month situation of no local infections. In response, residents in Chengdu actively participated in nucleic acid testing for SARS-CoV-2. On November 5, a male who took part in the testing was infected with SARS-CoV-2. Subsequently, 10 cases were confirmed in the high-rise building where he lived, even though most of cases lived on different floors but the same vertical orientation. Epidemiological investigation and environmental testing results suggested the possibility of long-range aerosol transmission in this outbreak. Following the epidemiological investigation and environmental testing, our study aimed to explore the mode of long-range aerosol transmission and identify potential key factors affecting the transmission of SARS-CoV-2 infection in this outbreak. To achieve this, we conducted an environment investigation and measured the dispersion of a tracer gas in the drainage system of the building to assess the plausibility of aerosol transmission of SARS-CoV-2.

Methods

Environmental investigation

Detailed information was collected on structural layout of the building, ventilation and drainage systems by direct exploration. In addition, we reviewed closed-circuit television camera records from the public elevators to determine usage patterns between October 28 and November 4. In this paper, the term "flat" is used to refer to an apartment unit. "Flat #" specifically refers to a particular flat number, whereas "-# flats" refers to a vertical column of flats in a high-rise building.

Epidemiologic analysis

We conducted an epidemiologic analysis to investigate the SARS-CoV-2 outbreak in a residential building. We collected data on symptom onset, demographic information, travel and exposure history, and other symptoms from the 11 infected residents, who were diagnosed with COVID-19 through throat swab and reverse transcriptase polymerase chain reaction (RT-PCR).

Statistical analysis

We utilized *WPS* 2019 to manage the data and software *R* 4.0.3 for statistical analysis. Enumeration data was expressed as a percentage or proportion, and a chi-square test was employed to compare the data. Statistical significance was defined as $P < .05$.

RT-PCR and next-generation sequencing (NGS)

To identify all close contacts of the infected individuals and assess the extent of environmental contamination by SARS-CoV-2, we conducted a comprehensive investigation between November 5 and November 10. Throat swab samples were collected from a total of 223 individuals residing in the building, including the 11 infected patients, 195 other residents, and 17 building management staff. In addition, we obtained 337 surface samples including ones wiping for floor drains, door handles, ventilation fans and so on in the 7 flats where the infected cases resided, as well as public areas and the building's drainage systems. To extract viral RNA from the collected specimens, we used Purelink Viral RNA/DNA kits (Invitrogen, USA) and a SARS-CoV-2 assay kit approved by the China Food and Drug Administration (CFDA). A positive result was defined as a cycle threshold value ⩽40.0. Furthermore, we employed NGS technology to determine the whole genome sequence of all SARS-CoV-2 positive samples. The positive samples were sequenced using the Illumina MiniSeq Sequencing platform with commercial SARS-CoV-2 whole-genome multiplex PCR kits (MicroFuture, Beijing, China) and the Nextera XT DNA Sample Preparation and Index kit (Illumina, San Diego, CA, USA). The obtained data was analyzed using CLC Main workbench 11.0 (QIAGEN, Dusseldorf, Germany). The Neighbor-joining Phylogeny tree was constructed by Mega 7.0.26[15] along with the gene sequences of China at the same time obtained from GISAID.[16]

Experimental tracer gas measurements

The flats on different floors are vertically connected through the kitchen and bathroom drainage systems, as well as the kitchen venting system. Water seals in the kitchen drainage system and backflow valves in the kitchen venting system limited aerosol transmission. To investigate possible aerosol transmission, we conducted tracer experiments on November 10 2021 using CO_2 as a tracer gas in the bathroom drainage system. We released approximately 0.1 MPa of CO_2, produced by mimicking the pressure when people sneeze, into the water-filled toilets for daily use and floor drains of the bathrooms. CO_2 concentrations were measured by a gas detector (PGM-6208, RAE system) at beginning of the experiment in Bathrooms 602, 902, 1002, 2002, and 2402. After respectively releasing CO_2 into toilets and the floor drains of the bathrooms in Flat 402 for 30 minutes, CO_2 concentrations were monitored in vertically master Bathrooms 602, 902, 1002, 2002, and 2402. We then compared tracer gas concentrations through floor drains and toilets in the vertically aligned -02 flats to assess the potential transmission pathways of SARS-CoV-2. The bathroom doors and windows were kept closed during the CO_2 release process. However, during CO_2 concentration monitoring, they were kept open to prevent anoxic asphyxia.

Results

Environmental investigation results

The building located in C District of Chengdu comprises 24 floors and is resided by 206 residents. There are a total of 88 flats in the building, with 4 located on each floor (namely flats 01, 02, 03, and 04) on floors 3 to 24. Different floors are connected by public elevator lobbies and corridors. The flats on different floors are vertically connected to each other through kitchen and bathroom drainage systems, as well kitchen venting system. In terms of ventilation, the building lacks a centralized air conditioning or fresh air system. Instead, each room is equipped with one or several windows. The toilet and floor drain in each bathroom are connected to a shared sewer line. Each bathroom is equipped with a ventilation fan that is linked to outside air by a circular hole in the wall, instead of ventilation pipelines.

Epidemiologic analysis results

The outbreak occurred in the building, resulting in 11 confirmed cases in 7 families. All 6 infected families lived in vertically aligned -02 flats (Flats 402, 602, 902, 1002, 2002, 2402), and only 1 family, residing in Flat 2401 on the same floor as

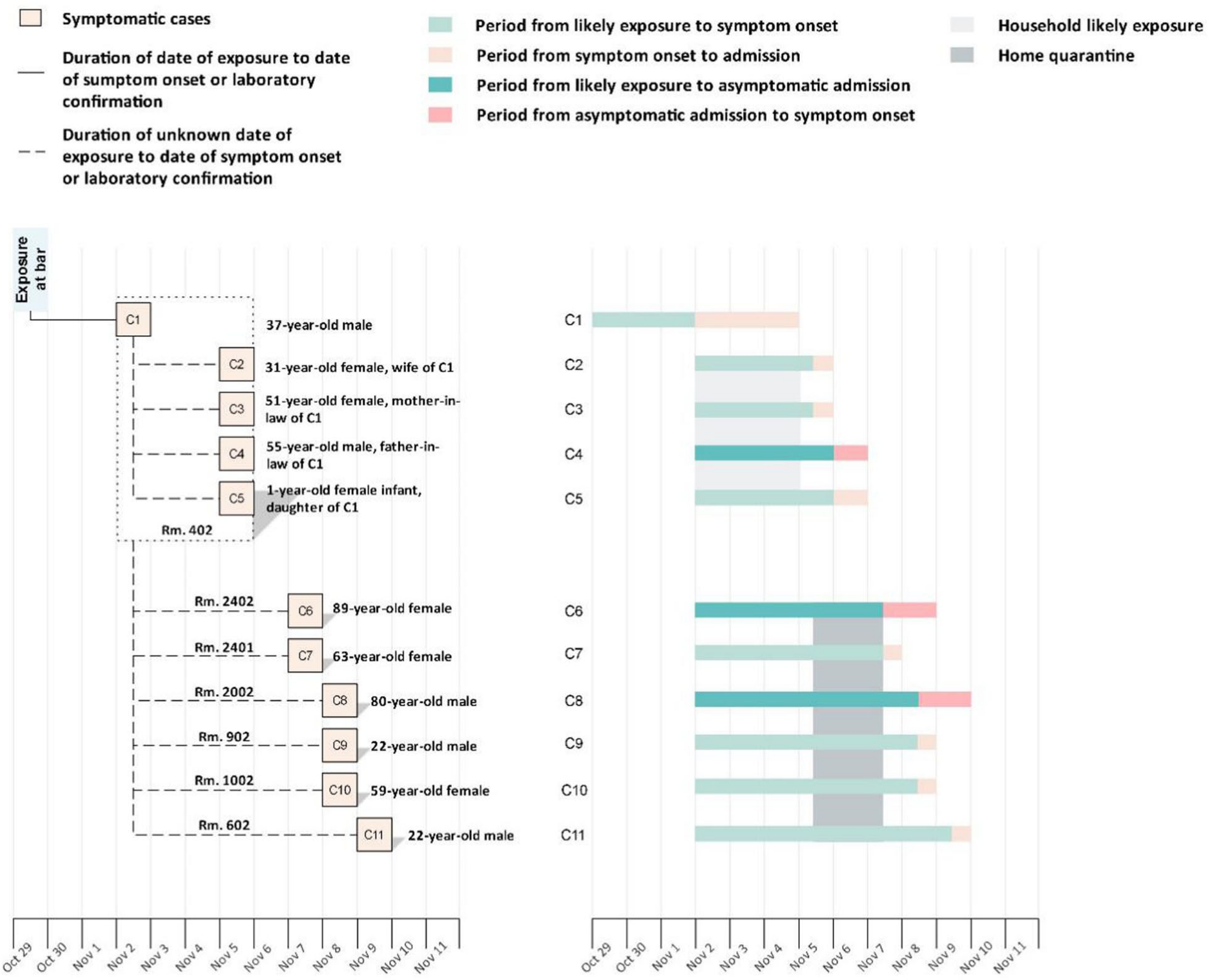

Figure 1. Epidemiological information of 11 confirmed cases.

Flat 2402, was infected. The first incidence occurred in Flat 402, where a 37-year-old male (C1) presented with fever, cough, and nasal congestion on November 2. He (C1), his wife (C2), mother-in-law (C3), father-in-law (C4) and his 1-year-old daughter (C5) were confirmed positive on November 5. On November 7, an elderly female (C6) residing in Flat 2402 and another elderly female (C7) residing in Flat 2401 were confirmed positive. On November 8, an elderly male (C8) living in Flat 2002, a male student (C9) living in Flat 902, and an elderly female (C10) residing in Flat 1002 were all confirmed positive. On November 9, a male student (C11) living in Flat 602 was confirmed positive. Figure 1 shows the epidemiological information of the 11 confirmed cases.

According to the epidemiological investigations carried out by the Center for Disease Control and Prevention (CDC), it was revealed that neither the 11 confirmed cases nor their families had any history of travel 14 days before the onset of symptoms. However, the index case, C1, went to a bar in Chengdu for a drink with his friends on October 29, where he was infected to SARS-Cov-2 by a confirmed case from Chongqing, China. Closed-circuit television camera records from the 2 public elevators showed that none of the cases had shared the elevator with each other, except for the index case's family, within 14 days before the symptom onset. Furthermore, the 6 neighbors and the index case's family members denied having any face-to-face contact within the same 14 days before the symptom onset.

Statistical analysis results

Out of the 50 residents living in −02 flats, 5 were infected with SARS-CoV-2, whereas only 1 out of the 151 residents living in other flats was infected, except the index case's family. Similarly, the incidence rate among residents living in −02 flats was significantly higher compared to those living in other flats ($\chi^2 = 8.32$, $P = .004$). The incidence rates of different household types were shown in Table 1.

RT-PCR and NGS results

Environmental testing was conducted in both the households of the cases and public areas after their diagnoses were

Table 1. The incidence rate of different household types.

DIFFERENT HOUSEHOLD TYPES	EXPOSED NUMBER	INFECTED NUMBER	ATTACK RATE (%)
−02 flats	50	5	10.00
−01, −03 and −04 flats	151	1	0.66
Total	201	6	2.98

Table 2. RT-PCR results of environmental samples from cases' homes.

ROOMS	LIGHT SWITCHES	DOOR HANDLES	DESKS AND SOFAS	DINING TABLES	FLOOR DRAINS IN BATHROOMS	KITCHENS	VENTILATION FANS
402	+	+	+	+	+	−	−
602	−	−	−	−	+	−	−
902	−	+	−	−	−	−	−
1002	−	−	−	−	+	−	−
2002	−	−	−	−	−	−	−
2401	+	+	+	−	−	+	−
2402	−	−	−	−	−	−	−

confirmed. The results showed that specimens taken from the interior of the elevators tested negative for SARS-CoV-2, but the button outside the elevator on the fourth floor, where the index case's family lived, tested positive for the N gene. All specimens taken from Flat 2002 and Flat 2402 tested negative, while some from Flat 402, Flat 602, Flat 1002, and Flat 2401 tested positive. Furthermore, samples collected from the floor drains in the bathrooms of Flat 402, Flat 602, and Flat 1002 tested positive. The index case's household had the highest number of positive cases and positive samples in the household environment. However, samples taken from the bathroom ventilating fans in the cases' households were negative for the virus. The results of RT-PCR testing of the environmental samples from the cases' homes are presented in Table 2, and the spatial distribution of cases and the locations of SARS-CoV-2 contamination are indicated in Figure 2.

NGS results showed the sequence coverage (30×) varied from 91.88 to 99.63 and the median sequence reading depth varied from 1052.17 to 50939.68. The whole genome sequences of virus collected from all 11 cases belonged to Delta variant (AY.126), sharing about 48 mutations compared with the reference strain MN908947.3, which was different from the variants (AY.122\AY30\B.1.617.2) prevalent at the same time in China. The neighbor-joining phylogeny tree is presented in Figure 3.

Results of experimental tracer gas measurements

At the outset of the experiment, the CO_2 concentration ranged from 396 to 402 parts per million (PPM) in Bathrooms 602, 902, 1002, 2002, and 2402. To investigate the possibility of aerosols entering the bathrooms through drainage stacks, we continuously released tracer gas into the water-filled toilet in Bathroom 402 for 30 minutes. After releasing CO_2 into water-filled toilet for 30 minutes, concentration of CO_2 remained constant at the baseline level. However, after releasing CO_2 into the floor drain for 30 minutes, our monitoring revealed significant tracer gas concentrations in all of the studied flats. The concentration of CO_2 in all the bathrooms exceeded the capacity of the gas detector, measuring above 5000 PPM. Moreover, we observed that the floor drains in Bathrooms 602, 902, 1002, 2002, and 2402 were dry. Figure 4 simulated the directions of aerosols movement in high-rise buildings.

Discussion

Aerosols are tiny particles as a mode of transmission, less than 5 μm in size, that can stay suspended in the air or gas for extended periods and penetrate deeply into the respiratory system, reaching the bronchioles and alveoli.[17,18] Studies suggest that these aerosols can also carry infectious SARS-CoV-2 and remain infectious and suspended in the air for hours.[19,20] Moreover one study has indicated that many viruses can attach to sewer biofilms, potentially creating opportunities for their later release.[21] Despite the acknowledgment by the World Health Organization (WHO) of the potential for aerosol transmission of SARS-CoV-2, no definite preventive measures have been recommended as of yet. A number of experimental studies conducted tracer gas measurements to simulate the movement of infectious aerosols.[22,23] To investigate the possibility of long-distance aerosol transmission of COVID-19 in a

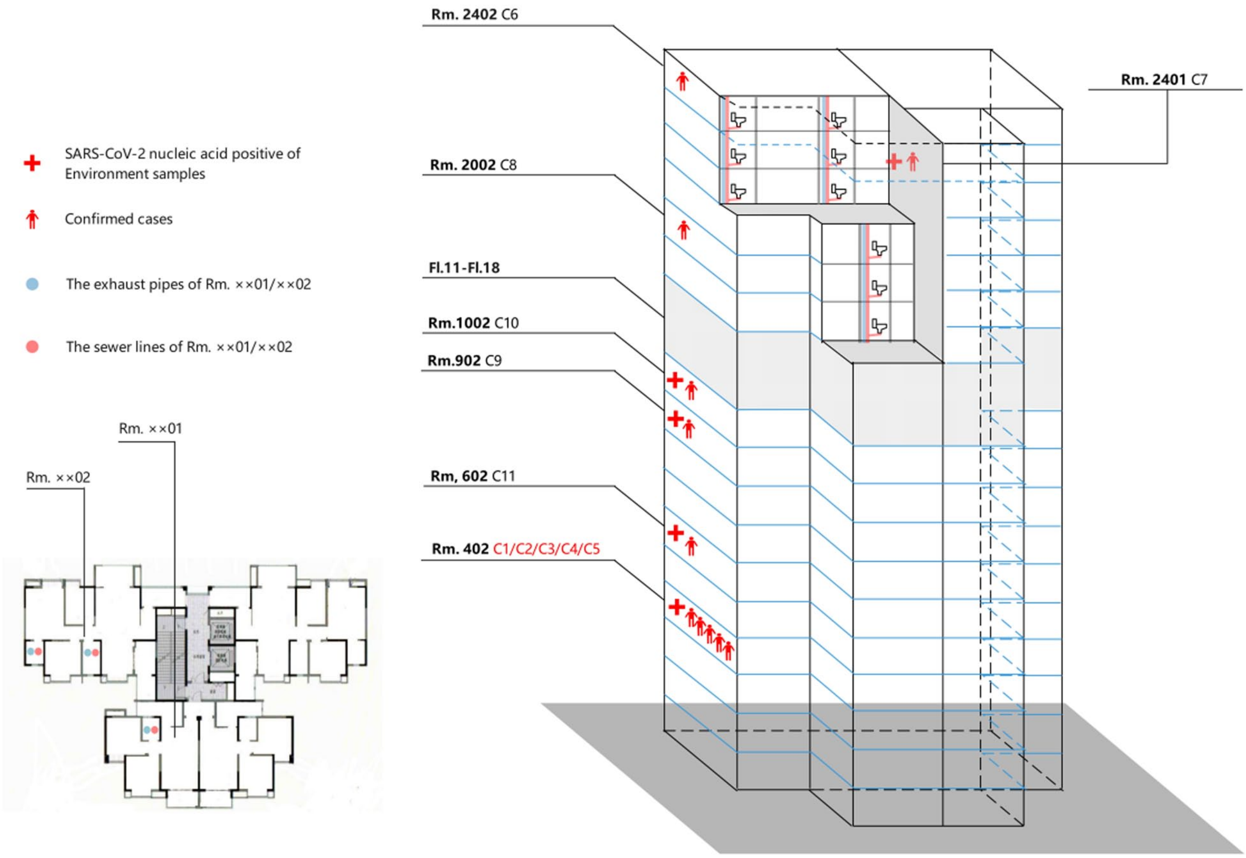

Figure 2. Spatial distribution of cases and the locations of SARS-CoV-2 contamination.

high-rise building where an outbreak occurred, we conducted tracer experiments and used NGS technology to confirm that each case was part of the same chain of infection. This evidence is crucial to establish the role of aerosol transmission in this particular outbreak.

Based on our epidemiological and environmental data, we have identified the index case (C1) living in Flat 402 as the source of the outbreak. C1 transmitted SARS-CoV-2 to his wife, daughter, parents-in-law through close contact during their daily lives. Then their 6 neighbors were infected. It's noteworthy that 5 out of the 6 infected neighbors lived in –02 flats, which were of the same type and orientation as C1's flat on different floors. Most of the cases in this outbreak were vertically distributed, making it improbable that structural cracks could vertically extend beyond 20 floors. Therefore, it is improbable that long-range aerosol transmission resulted from multiple structural cracks. Environmental data revealed that the elevators in the high-rise buildings were not contaminated, but C1' s flat was heavily contaminated with SARS-CoV-2. The flats on different floors are vertically connected through the kitchen and bathroom drainage systems, as well as the kitchen venting system. Although SARS-CoV-2 contaminated the kitchen of Flat 2401, water seals in the kitchen drainage system and backflow valves in the kitchen venting system limited aerosol transmission. However, environmental data revealed that SARS-CoV-2 was present in the floor drains of the bathrooms in flats 402, 602, and 1002, indicating the possibility of contamination in the pipelines of the bathroom's drainage system. Therefore, the focus of the investigation was on the floor drains and sewage pipes to determine the cause of the outbreak. Tracer gas is a suitable surrogate of exhaled droplet nuclei for studying airborne transmission in the built environment.[24] We conducted an experiment using tracer gas and released it into both bathroom floor drains and water-filled toilets, which shared the same sewer line. The results demonstrated that there is vertical connectivity from the fourth floor to the 24th floor through floor drains. When CO_2 was injected into the water-filled toilet, some of it dissolves in the water, while some could not pass the water seal and was released into the bathroom air. The outbreak occurred during the winter season in Chengdu, where people showered less often due to the low temperatures with drier floor drains in the bathrooms and poor ventilation. In our outbreak investigation, we found that dry floor drains might facilitate the transmission of viral aerosols through the bathroom sewage system. This vertical transmission route is consistent with the findings of Guo et al, who reviewed several vertical COVID-19 outbreaks in high-rise buildings in China and South Korea.[25]

Epidemiological data from our investigation also suggested that transmission was more likely to occur on higher floors. Kang et al used ethane as a tracer gas in a similar study and found that the concentration of ethane was highest on the

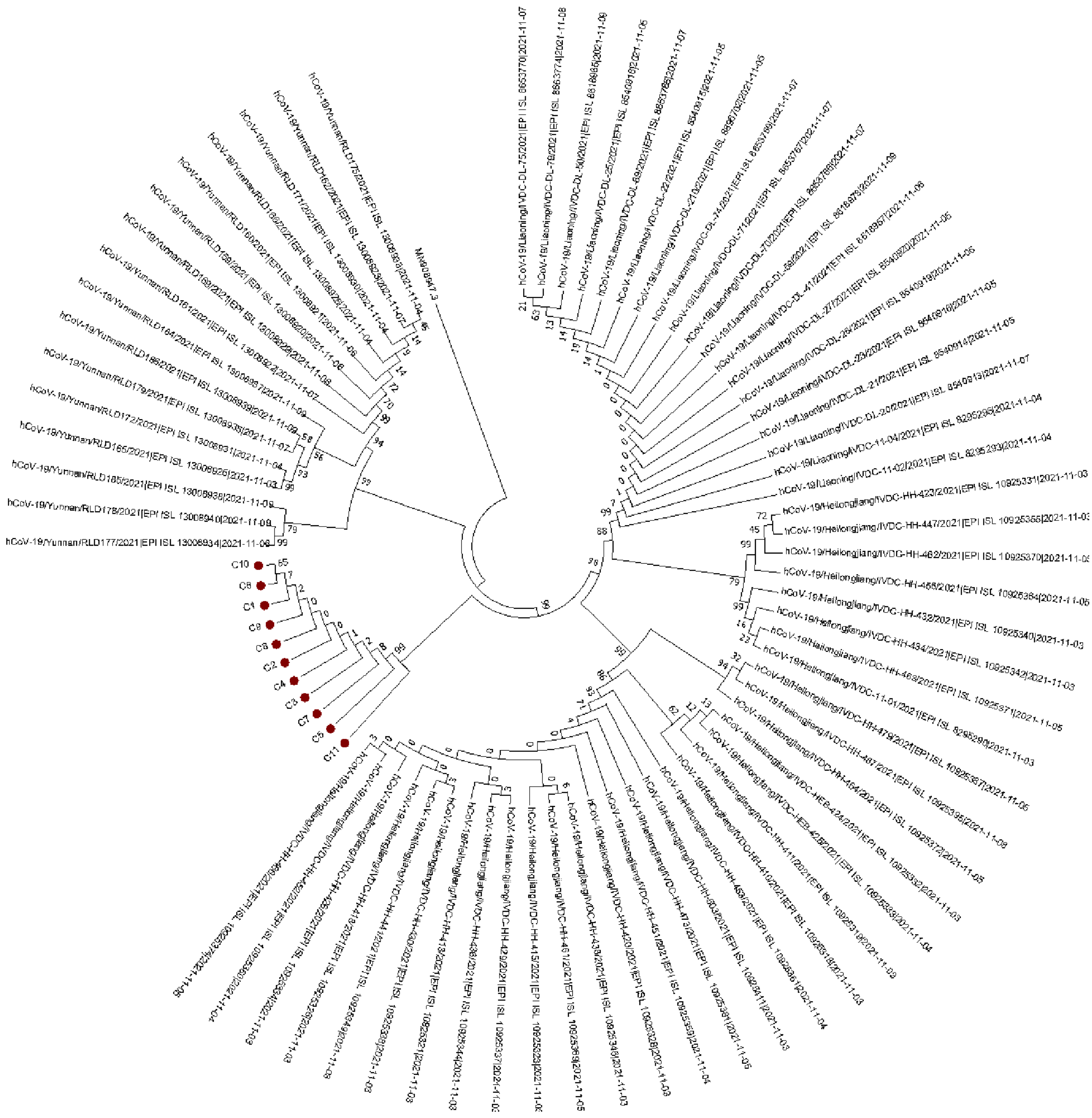

Figure 3. Neighbor-joining Phylogeny tree.

highest floor where the infected case lived.[11] According to Guo et al the transient movement of aerosols in the drainage system may be the result of various factors, including dry floor drains, the chimney effect caused by buoyancy, and pressure differences in the stack. Once in the air, they can spread through underutilized sinks, showers, bathtubs, or sluices, driven by pressure differences between the sewer pipe and living spaces, posing a serious threat. However, it is also possible for air to move down the stack when entrained by falling wastewater.[26] In this outbreak, the source of infection was located on lower floors, while cases infected by the source were found on higher floors, which is consistent with the results of Kang and Wang.[11,13] However, in the vertical outbreak that occurred in Korea during the summer, more infected cases were found on floors below the infected source, indicating that in summer, as the temperature inside is lower and the density is higher than outside, the air inside the building moves to the lower part by receiving a downward force. During winter the temperature inside is higher and the density is lower than outside, the air inside the building moves to the higher part by receiving an upward force. In addition to the chimney effect, the wind at both the manhole and roof top and exhaust fans in the associated bathrooms can affect the driving pressure of natural ventilation.

Kang's study suggested that fecal aerosols were responsible for transmission in high-rise buildings, we believe that the main source of aerosols should be respiratory aerosols. In this outbreak no cases of diarrhea were reported, but some individuals experienced symptoms such as fever, cough, and nasal

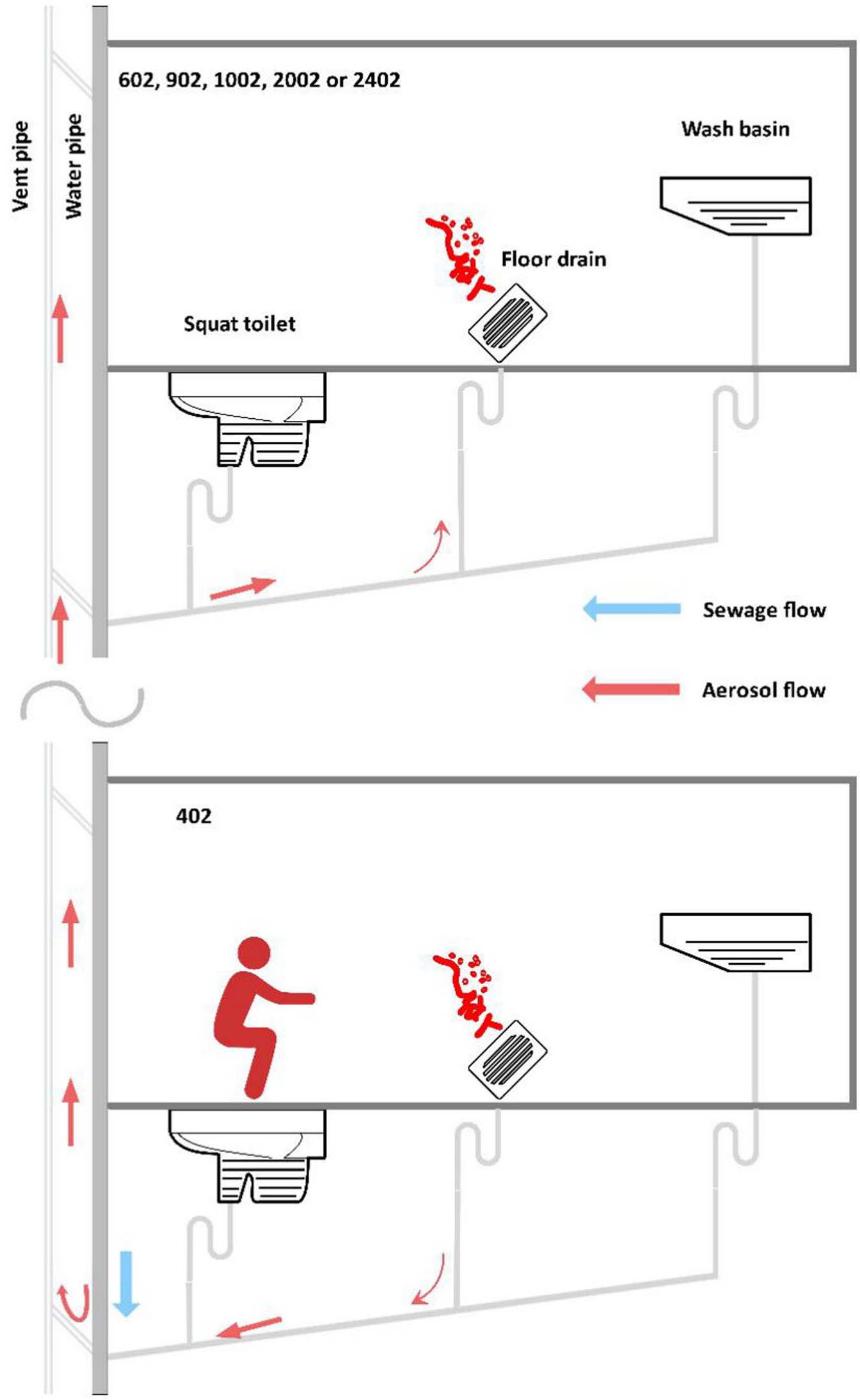

Figure 4. The directions of aerosol movement in high-rise buildings.

congestion. It is likely that feces contained a lower viral load of SARS-CoV-2 compared to nasal/oral secretions in this outbreak, meanwhile studies have suggested that viable virus particles may be more prevalent in nasal mucus, saliva, and sputum of infected individuals.[27-31] Our environmental sampling indicated positive specimens only in the floor drains, and not in the toilets. Furthermore, our tracer experiments showed that gases released into the toilet water could not reach other floors, suggesting that airborne transmission through toilets was unlikely in this outbreak.

Thus, we infer that the index case's family members likely transmitted the virus through aerosols while using the bathrooms, that is, when they sneeze, cough, breathe, or sing, around the time when the symptoms emerged. The virus can be transmitted through aerosols in humid environments, which are conducive to the survival and spread of SARS-CoV-2. In winter, the indoor temperature is relatively higher and the air density is lower than the outside environment, causing the air to move upwards inside the building. As a result of the chimney effect, virus-laden aerosols originating from the fourth floor spread primarily to the upper floors in a linear manner along the drainage system. Ultimately, individuals using the bathroom are susceptible to inhaling the aerosols. In this outbreak, C7, the elderly patient in Flat 2401, reported that she had not been in close contact with any other confirmed cases within 14 days before symptom onset. Closed-circuit television records from the 2 public elevators showed that she did not share an elevator with any other confirmed cases. It is possible that she might have had close contact with the patient in Flat 2402 within 14 days before symptom onset, since they resided on the same floor and possibly shared common areas like the elevator hall. However, due to her advanced age, she could not provide details about this contact.

However, this study has some major limitations that need to be addressed. To simulate human sneezing, we used pressurized carbon dioxide as a tracer gas in the experiments. However, pressurized CO2 has properties that differ from the aerosols exhaled by people. It is a high-speed gas jet with a very low density and high flow velocity. In contrast, aerosols exhaled by people have a slower flow velocity, higher density, and longer residence time in the air, which makes them more prone to spreading the virus. Further research and confirmation are essential to comprehensively understand the dissemination and distribution of virus-laden aerosols within drainage system pipelines. However, due to the advanced age of the patient living in Flat 2401, she was unable to recall the full details of face-to-face contact, hence making it challenging to accurately determine the mode of transmission of her infection.

Conclusion

On the basis of circumstantial evidence, long-range aerosol transmission may have contributed to the community outbreak of COVID-19 in this high-rise building. The dry condition of floor drains may be a significant factor in the long-range dissemination of virus-laden aerosols in these buildings. The vertical transmission of diseases through aerosols in high-rise buildings demands urgent attention.

Author Contributions

Xiaoman Jiang and Yong Yue contributed to the idea of the study, organized the field experiment and wrote the draft; Chenlu Zhao and Yuezhu Chen performed data analysis and visualization; Xufang Gao, Qinlong Zhang and Changxiong Li performed the field tracer experiment; Zhenhua Chen, Weiwei Huang and Wenjun Xie performed the RT-PCR and NGS test; Xiaoyan Zhao and Zhijian Liu conducted the epidemiologic investigation and environmental investigation.

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