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Vertical outbreak of COVID-19 in high-rise buildings: The role of sewer stacks and prevention measures

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Abstract

COVID-19 outbreaks in high-rise buildings suggested the transmission route of fecal-aerosol-inhalation due to the involvement of viral aerosols in sewer stacks. The vertical transmission is likely due to the failure of water traps that allow viral aerosols to spread through sewer stacks. This process can be further facilitated by the chimney effect in vent stack, extract ventilation in bathrooms, or wind-induced air pressure fluctuations. To eliminate the risk of such vertical disease spread, the installation of protective devices is highly encouraged in high-rise buildings. Although the mechanism of vertical pathogen spread through drainage pipeline has been illustrated by tracer gas or microbial experiments and numerical modeling, more research is needed to support the update of regulatory and design standards for sewerage facilities.

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COVID-19, SARS-CoV-2, Sewer, High-rise building, Wastewater, Fecal-aerosol-inhalation.

Introduction

During the coronavirus disease-19 (COVID-19) pandemic, severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) viruses have been spread around the world causing respiratory symptoms, pneumonia, and deaths [1,2]. Many national governments limited social interactions and restrained economic activities to mitigate COVID-19 transmission, leading to isolation and hardship. The rapidly emerging new variants of concern, such as Delta and Omicron, create new challenges for countries even with a high vaccination rate [3].

The highly contagious SARS-CoV-2 exploited many routes to be transmitted among people, including human-to-human transmission under close contact by sprayed large droplets, or aerosol inhalation, and fomite transmission by touching contaminated surfaces with viral deposition [4]. In addition, SARS-CoV-2 viruses are excreted into the stool of infected individuals and enter sewers after toilet flushing [5,6], as confirmed by the detection of SARS-CoV-2 gene markers in wastewater samples globally [7–13]. Many countries have implemented routine wastewater surveillance programs for the presence and concentration of SARS-CoV-2 in different sewer catchments or wastewater treatment plants (WWTPs) [14–16]. Hence, the wastewater in sewers is also a potential transmission vehicle for SARS-CoV-2.

The possibility of fecal-oral transmission has been proposed and discussed widely [17–23], supported by the isolation of viable viruses from human feces [24]. Apart from fecal shedding, other sources containing active SARS-CoV-2 viruses, including sputum, nasal mucus, blood, and saliva, may also enter the wastewater in sewers [25–27]. Some strains of coronavirus could preserve infectivity in bulk wastewater for a few days [28,29], and in sewers for hours [30], thus potentially making small sewage droplets as a transmission pathway of COVID-19.

High-rise apartment buildings are common residential arrangements in many densely populated cities worldwide. The flats/units of high-rise buildings are usually connected to the same drainage system. This makes it possible that the aerosolized viral particles generated from toilet flushing can be transmitted through sewer stacks, including linked sewage and ventilation pipes [31–33], causing infections distributed vertically in the building towers linked with the same sewer stacks. This paper reviewed the reported cases of vertical outbreaks of COVID-19 and studies related to the viral transmission mechanisms in sewer stacks of high-rise buildings, most of which are within the last two years. Based on this, some recommendations and research needs were proposed for preventing the transmission of COVID-19 in high-rise buildings.

Vertical outbreaks of COVID-19

The vertical outbreak came into the spotlight as a serious severe acute respiratory syndrome (SARS) outbreak that happened back in 2003 at a private residential apartment in Hong Kong, resulting in 42 deaths and 321 infected cases [34]. For the current COVID-19 pandemic, 15 vertical outbreaks in residential buildings were reported in Hong Kong and Guangzhou, China [35,36], and one outbreak in Seoul, South Korea [37] (Table 1). The infected cases were detected along the vertical line in the buildings connected by the same plumbing pipe. Moreover, most of the secondary infections resided on upper floors above the index case (Table 1). Additionally, the high risk of in-building infection is also a considerable concern for quarantine hotels and hospitals, where infected people frequently discharge viruses into the interconnected drainage system [38,39]. Therefore, it is likely that there have been more unrecognized vertical outbreaks as well.

How did it happen?

Initially, the wastewater plumbing system was identified as a possible transmission pathway for SARS in 2003 at Amoy Garden by WHO [40]. The defect of empty U-bends in bathrooms or damaged sewer pipes was blamed to facilitate the transport of virus-laden aerosols into habitable space, which was aided by bathroom extract fans drawing contaminated air from depleted floor drains or bathtubs into households [41,42]. The U-bends (or U-traps) are common in building sanitary systems functioning as physical barriers to seal the connection between the riser and the fixture when filled with water [34]. However, if the water seal is dried out, the suspended virus-laden aerosols from wastewater may escape through the open channel into other bathrooms thus causing infections vertically in the connected flats [35]. Furthermore, the sewer stack (ventilation and drainage pipework) at Amoy Garden was a cross-connected system with the wet stack for all appliance discharges and the vent stack linked together [43]. Thus, the ventilation might also play a role in disease spread within or even between the building blocks/towers while wind currents carried the virus-laden aerosols into adjacent flats through open windows [44–46].

In response to such a hypothesis, experimental investigations using pilot sewer stacks [44,47], tracer gases studies in buildings [35,36,48,49], and mathematical simulation [50,51] were conducted to delineate how the vertical outbreak occurred. Figure 1 provided a summary of the vertical outbreak mechanisms showing

Table 1

Summary of reported vertical outbreaks of COVID-19 in high-rise buildings.

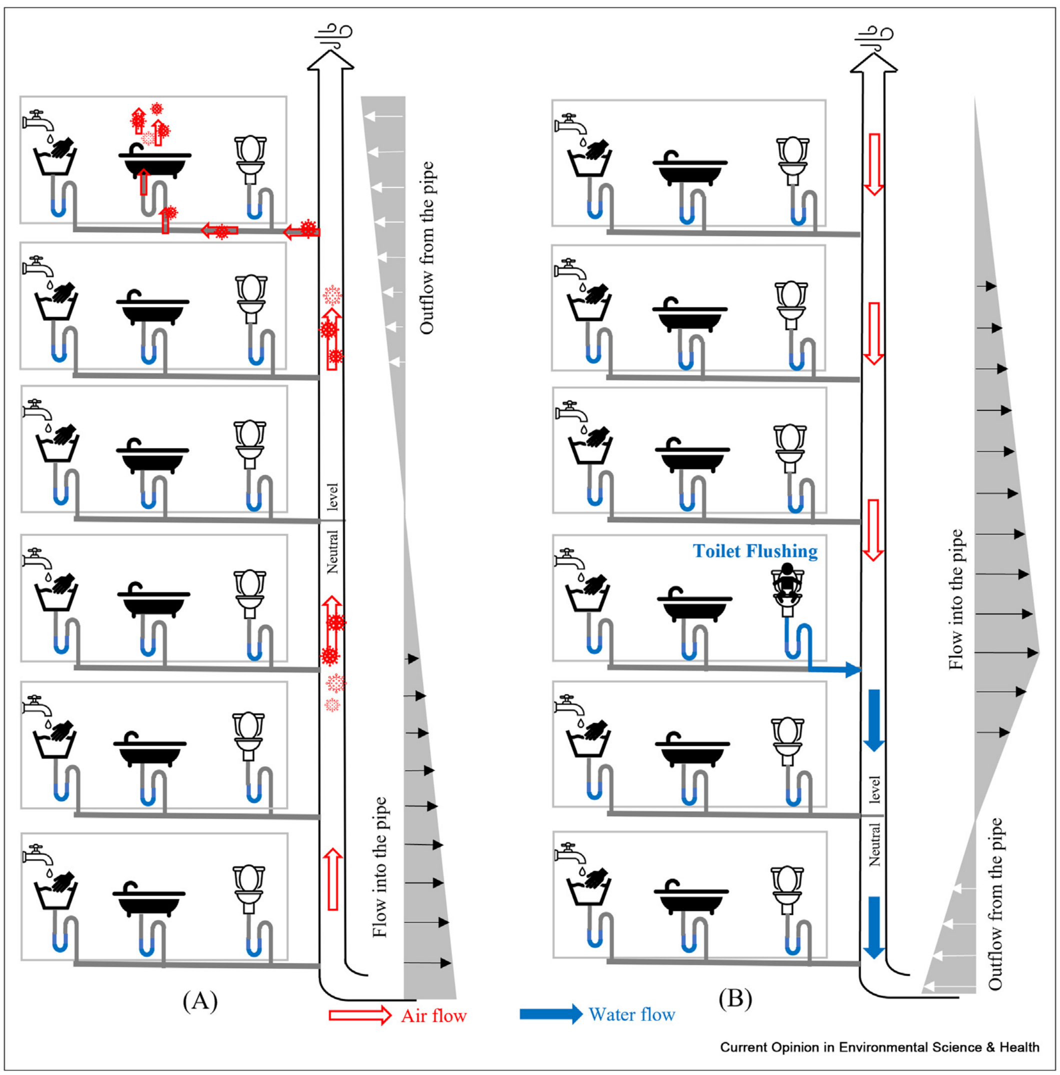
Time	Location	Infected cases	Case distribution	Reference
February 2020	Guangzhou, China	9	Flat 1502 on 15th floor – first infection with 5 cases Flat 2502 on 25th floor – second infection with 2 cases Flat 2702 on 27th floor – third infection with 2 cases	[35]
March 2020	Heng Tai House at Fu Heng Estate , Hong Kong	3	Flat 13 on the 32nd floor – first infection with 2 cases Flat 13 on the 34th floor – second infection with 1 case	[35]
June 2020	Luk Chuen House in Sha Tin, Hong Kong	7	Flat 812 on the 8th floor – first infection with 1 case Flat 710, 810, 1012, and 1112 on 7th, 8th, 10th, and 11th floor – secondary infection with 6 cases	[35]
August 2020	Seoul, South Korea	10	Flat A on 6th floor – first infection with 3 cases Flat A on 4th, 5th, 10th, 11th floor and Flat B on 2nd, 11th floor – secondary infection with 7 cases	[37]
January 2021	Kensington Plaza Building in Kowloon Bay, Hong Kong	14	Flat 5C on 5th floor – first infection with 6 cases Flat 6C, 7C,17C, 5 A, 6D on, 5th, 6th, 7th, 17th floor – secondary infection with 8 cases	[36]
February 2021	Wai Lee Building in Quarry Bay, Hong Kong	9	Flat 1404 on 14th floor – first infection with 4 cases Flat 1704, 1811, 2104, 1405 on 14th, 17th, 18th, 21st floor – secondary infection with 5 cases	[36]

the possible route of virus-laden airflow and the pressure profiles of non-flushing periods and flushing periods, respectively. The airflow in red arrows happens both in the vent stack and wastewater pipes.

Virus-laden aerosols could be generated due to hydraulic interactions between wastewater flush and the surrounding stack pipe [47], an interaction that was confirmed by tracer organism experiments in a two-story sanitary plumbing test rig. Cultured inoculums were flushed into the test rig on the lower floor, and cross-transmission was then detected in air and surface samples collected on the upper floor [47]. In addition, a SARS-CoV-2 positive sample collected inside the washbasin U-bend in a flat connected to the index infection also supports the bio-aerosolization of wastewater (mixed with stool and exhaled mucus) produced by the index infection and its subsequent transmission along drainage pipes [35].

The leak of virus-laden aerosols is a combined result of depleted U-traps, the chimney effect (due to buoyant force), and pressure difference in the stack (Figure 1). As shown by the measured tracer gas concentration along the dried-out floor drains in bathrooms, virus-laden aerosols in the airstream would mainly flow toward upper floors above the injection location, attributed to chimney effect [35,36] (Figure 1a). Then, it goes through defective traps, dried floor drains, little-used sinks, showers, bathtubs, or sluices, driven by

Figure 1



The wastewater flow, air flow of viral aerosols, and the pressure profiles of no-flushing period (**a**) and flushing period (**b**) of sewer stacks in high-rise buildings. The horizontal black ($\Delta P<0$) and white ($\Delta P>0$) arrows with shade represent the pressure difference (ΔP) between the inside and outside of the stack. The red and blue arrows indicate the flow of contaminated air and wastewater, respectively as adapted with modifications from Kang et al. [35] and Zhang et al. [51]. Flow of virus-laden air through a dried U-trap (grey line) into the bathroom is also illustrated.

pressure differences between inside sewer pipe and habitable space, thus posing a threat. Air may also move down the stack if subjected to entrainment by the falling wastewater as shown in Figure 1b [50,52]. Most of the time (non-flushing periods), the aerosolized pathogens travel from horizontal collection drains, through wastewater pipes or the vent stack, and toward the cowl on rooftops under natural buoyancy forces (Figure 1a).

The chimney effect and pressure difference might be influenced by temperature/humidity differences, wind shear across stack cowl (gas vent) on rooftop to manholes at building bottom, and floor heights [35,36]. Numerical simulation indicated that upper floors experience a much higher leakage risk of sewage aerosols through floor drain without an efficient water seal, which is caused by more positive air pressure ($\Delta P>0$) in the stack during non-flushing periods [51] (Figure 1a). However, in toilet flushing events, the probability of positive pressure is associated with the wastewater flow rate or discharge height, and the flow-generated pressure can propagate toward the ventilation exit at top of the roof [50]. In addition, the wastewater volume for toilet flushing has a negligible impact on drainage airflow in vertical pipes [51,53].

Depleted U-traps are due to evaporation or pressure propagation of air surges inside vent stacks. Both the positive and negative pressure transient or siphonage can displace water-trap seals and allow air movement or bubble ejection from sanitary pipes to household space [53,54]. Higher buildings are more prone to such a problem of depleted U-trap since the self-siphonage tends to happen at high-rise buildings with more than 30 stories [44]. Moreover, induced siphonage may be also caused by the chimney effect or external air pressures (wind shear/sewer surcharge/powerful extract ventilations). When combined with the exhaust fans in bathrooms, the suck-in effect induced by negative pressure inside the room can affect the driving force of airflow and thus increase the risk of viral dispersion [36].

In addition, there are other potential factors which might lead to the virus transmission in the flat space. For instance, running of exhaust fan at night or when unattended could increase the risk of sucking virus-laden aerosols into the bathroom. The aerosols may subsequently leak to habitable space via bathroom door. Similar to the bathroom, an oversized exhaust fan could possibly create large pressure differentials, resulting in significant backflows that draw virus-laden air into kitchens and contaminate food and kitchen utensils. Furthermore, the laundry wastewater generated from cleaning the virus-laden clothes likely serves as a potential SARS-CoV-2 transmission pathway. Usually, laundry wastewater is combined with the black wastewater. Even laundry wastewater is collected and transported in separate pipelines, similar processes described above for sewer stacks (Figure 1) may occur, producing virus-laden aerosols that can act as a transmission pathway when the air pressure facilitates its movement to habitable spaces. Therefore, multiple risks should be assessed and taken into consideration to prevent the vertical transmission of SARS-CoV-2 along plumbing systems.

How to prevent the vertical outbreak?

Given the drainage system as a reservoir for not only SARS-CoV-2 but also other transmissible human pathogens [55−57], the design and maintenance of sanitary plumbing in high-rise buildings require specific attention and professional guidance [58]. However, current drainage design guidelines for high-rise buildings are the same as traditional low-rise houses. The COVID-19 pandemic demonstrates that these guidelines need updating [31]. In terms of the sewer design regarding water traps, Kelly et al. [59] and Gormley et al. [43] proposed sonar-like devices to be installed in building drainage and vent system to remotely identify depleted trap seals by monitoring response to applied pressure pulse for a timely fix or replacement. Alternatively, installing deep-seal traps, auto-refilled water traps, trap-seal primer valves, anti-backflow valves, pressure attenuators at the off-set location, or other innovative devices is also recommended for future research [42]. Moreover, the risk of virus leakage along drainage pipes can be avoided if a negative environment is created at the cowl by incorporating a pump at an extra cost [51].

As for daily housekeeping, apartment residents should (i) be alert to unexpected odor in bathrooms or kitchens; (ii) pay attention to the cracks, leakages, blockage, or disconnection of the pipework and bubbles in sinks or toilets and check the controlled seal of sewerage pipe connections periodically, such as tees, ferrules, and other fittings that might be broken or leaking; (iii) keep all water appliances fitted with effective U-bends and fill floor drains, sinks, and bathtubs with water regularly [38]; (iv) deeply disinfect floor drains and bathroom with a diluted bleach solution to avoid the spread of infectious pathogens [34]; (v) ensure the bathroom fans are properly sized; (vi) install a louver on the toilet door to alleviate negative pressure. In addition, for old buildings over 40 years, the refurbishment and repairment should take the sanitary plumbing system into special consideration to achieve a healthy building environment [60]. Collectively speaking, precautionary measures should be practiced routinely in case of vertical disease spread, particularly in high-rise buildings with densely populated residences.

Overall, there are still significant research needed for further delineation and prevention of vertical disease spread in high-rise buildings. Although experimental studies employing tracer gases and model bacterial pathogens were conducted to demonstrate the upward aerosol transmission in sewer stacks, the evidence of infectious virus transmission through sewers remains absent to date. Numerical modeling helped with delineating the dynamic mechanism behind viral transportation in drainage systems, but the parameter calibration and model validation require more experimental data under different environmental conditions. Furthermore, the pressure propagation of air surges in high-rise buildings which leads to depleted U-traps was not sufficiently investigated yet. The effect of air surges might be depending on the diameter of sewer stacks, the volume or height of flushing water, and temperature variance in the plumbing pipes, while their detailed relationship has not been fully reported. Future research is highly recommended to address such knowledge gaps for a better understanding of the empty U-bend in high-rise buildings and improving prevention strategies.

Conclusions

- Vertical outbreak of COVID-19, due to the transmission through sewer stacks, has been reported in many high-rise buildings.
- The vertical outbreak is due to that toilet-flushing generated viral aerosols diffuse into different flats through faulty wastewater stacks. The spread of viral aerosols can be facilitated by bathroom extraction fans, wind shear, or temperature and humidity variances.
- Different measures can be implemented to seal the sewer stacks from the indoor atmosphere, such as deep-seal traps, auto-refilled water traps, pressure attenuators, etc.
- Research about the vertical outbreak is still limited to support the update of regulatory standards for designing sewerage facilities in high-rise buildings.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Nothing declared.

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