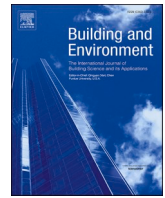




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Explosive outbreak of SARS-CoV-2 Omicron variant is associated with vertical transmission in high-rise residential buildings in Hong Kong

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ABSTRACT

The phenomenon of vertical transmission of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) in high-rise residential buildings (HRRBs) is unique in our densely populated cosmopolitan city. The compulsory testing of a whole building under the scheme of restriction-testing declaration (RTD) during the fourth wave (non-Omicron variant) and fifth wave (mostly Omicron variant) of COVID-19 outbreak in Hong Kong allowed us to study the prevalence of this phenomenon, which may represent a form of airborne transmission. From 23 January 2021 to 24 March 2022, 25,450 (5.8%) of 436,397 residents from 223 (63.0%) of 354 HRRBs under RTD were test-positive for SARS-CoV-2. Using the clustering of cases among vertically aligned flats with shared drainage stack and lightwell as a surrogate marker of vertical transmission, the number of vertically aligned flats with positive COVID-19 cases was significantly higher in the fifth wave compared with the fourth wave (14.2%, 6471/45,531 vs 0.24%, 3/1272; $p < 0.001$; or 2212 vs 1 per-million-flats; $p < 0.001$). Excluding 22,801 residents from 38 HRRBs who were tested negative outside the 12-week periods selected in fourth and fifth waves, the positive rate among residents was significantly higher among residents during the fifth wave than the fourth wave (6.5%, 25,434/389,700 vs 0.07%, 16/23,896; $p < 0.001$). Within the flats with COVID-19 cases, the proportion of vertically aligned flats was also significantly higher in the fifth wave than in the fourth wave (95.6%, 6471/6766 vs 30.0%, 3/10, $p < 0.001$). The proportion of HRRBs with COVID-19 cases was significantly higher during the corresponding 12-week period chosen for comparison (78.2%, 219/280 vs 11.1%, 4/36; $p < 0.001$). Whole-genome phylogenetic analysis of 332 viral genomes showed that Omicron BA.2 was the predominant strain, supporting the high transmissibility of BA.2 by airborne excreta-aerosol route in HRRBs of Hong Kong.

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1. Introduction

Since the emergence of coronavirus disease 2019 (COVID-19), the contribution of airborne transmission of the causative agent, severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) to this pandemic has received increasing attention [1]. Airborne transmission was first suspected in healthcare settings [2–5], and was further observed in restaurants and public transportation in the community [6–9], where people gathered in poorly ventilated or overcrowded indoor areas [10]. Airborne transmission of COVID-19 has been later clearly documented, especially during the outbreak due to the Omicron variant of SARS-CoV-2, to be associated with higher effective reproduction number than the Delta variant [11]. The recent emergence of Omicron subvariant BA.2 demonstrates the highest transmissibility among all reported variants. BA.2 is about 1.5 and 4.2 times more contagious than the BA.1 subvariant and Delta variant respectively [12]. Hong Kong is a cosmopolitan city of 1064 square kilometers with a hilly geography. It is characterized by densely built high-rise residential buildings (HRRBs) along the costal reclamation to accommodate its 7.5 million population. Many incidents of vertical airborne transmission of SARS-CoV-1 and SARS-CoV-2 due to shared lightwell (an unroofed external space provided within the volume of a large building to allow light and air to reach what would otherwise be a dark or unventilated area) or faulty sewage drains have been reported during the SARS outbreak in 2003 [13] and also during the COVID-19 outbreak [14–16]. Recently, the explosive spread of SARS-CoV-2 Omicron subvariant BA.2 has caused a single-source community outbreak in a housing estate, with a short doubling time of 1.28 days [17]. Here, we analyzed the COVID-19 outbreaks in Hong Kong, with specific focus on the clustering of cases in public and private HRRBs. We found a significantly higher incidence of suspected vertical transmission during the fifth wave, which was predominantly caused by BA.2. BA.2 is likely to have a higher propensity to cause airborne transmission by excreta (feces, saliva, nasal discharge and sputum)-aerosol particles through drainage pipe or lightwell of HRRBs than that of the previous virus strains.

2. Methods

2.1. Epidemiology of COVID-19 in Hong Kong

Soon after the official announcement of an outbreak of community acquired pneumonia in Wuhan, Hubei Province, China, on 31 December 2019 (day 1) [18], a comprehensive website was established to upload the epidemiological information of each confirmed COVID-19 case, including the demographics, date of symptom onset, date of reporting, location of residential building, and source of virus acquisition, by the Centre for Health Protection (CHP), Department of Health, the Government of Hong Kong Special Administrative Region, China [19]. The evolution of COVID-19 epidemic in Hong Kong can be retrospectively divided into different phases. The first wave (23 January 2020, day 44, to 14 March 2020, day 75) was predominantly caused by imported cases from mainland China with limited local transmission. The second wave (15 March 2020, day 76, to 30 June 2020, day 183) was predominantly caused by imported cases from western countries leading to some local transmission. The third wave (1 July 2020, day 184, to 31 October 2020, day 306) and the fourth wave (1 November 2020, day 307, to 30 April 2021, day 487) were dominated by local transmission of B.1.1.63 and B.1.36.27 lineages, respectively [20]. A near-elimination phase was observed between 1 May 2021, day 488, and 30 December 2021, day 731, when there were only rare sporadic cases without third generations of local transmission. The fifth wave was caused by SARS-CoV-2 Omicron variant (31 December 2021, day 732 onward). To control COVID-19 in Hong Kong, strict border control and quarantine measures have been implemented for inbound travelers [21,22], together with compulsory testing of high-risk occupations such as healthcare workers and contact tracing [23]. Stepwise enhancement of active surveillance

of SARS-CoV-2, from risk-based to universal admission screening, was adopted in healthcare settings [24,25]. Compulsory testing of all occupants in buildings at the specified and restricted areas were also implemented for the control of COVID-19 using a restriction-testing declaration (RTD) [26]. Persons within the restricted areas were required to stay in their premises and undergo compulsory testing arranged by the Government, and could only leave when the test results were mostly ascertained.

2.2. Restriction-testing declaration for residents in high-rise residential buildings

The practice of RTD was introduced during the fourth wave, since 23 January 2021 (day 390). An RTD can be issued to a restricted area in response to a confirmed case or detectable SARS-CoV-2 RNA in sewage surveillance [27]. The number of HRRBs with confirmed COVID-19 case (s) was retrieved from the website of CHP [28]. The results of RTD at the HRRBs were retrieved from press release statements from the website of the Government of Hong Kong Special Administrative Region [29]. The proportion of private and public HRRBs undergoing RTD and their positive rates in the fourth and fifth waves were analyzed. For the comparison between the fourth and fifth waves, a comparable period was selected in the fourth wave (28 January 2021 to 21 April 2021, 12 weeks) and the fifth wave (31 December 2021 to 24 March 2022, 12 weeks). The 12-week period chosen in the fourth wave included all HRRBs under the scheme of RTD except for two HRRBs with a total of 1900 residents who were tested negative for SARS-CoV-2 on 23 April 2021 and 29 April 2021 (at the end of the fourth wave).

2.3. Suspected vertical transmission of COVID-19 in high-rise residential buildings

The HRRBs with newly diagnosed COVID-19 cases detected under the scheme of RTD were analyzed. HRRBs contain many flats, which is defined as a living unit ranging from one to three bedrooms in size, located on the same floor of a building. The individual flats on different floors are labelled by alphabets or numbers to denote their spatial relationship which often indicates whether they share lightwell and drainage stack. We used the clustering of cases among vertically aligned flats with shared drainage stack and lightwell as a surrogate marker of suspected vertical airborne transmission (Fig. 1). The total number of flats with COVID-19 cases that were involved in suspected vertical transmission was recorded. The numbers of flats with suspected vertical transmission per million residential flats in Hong Kong in the fourth and fifth waves were calculated. The contribution of suspected vertical transmission to the total number of COVID-19 cases during 12-week period of comparison in fourth and fifth waves were also analyzed.

2.4. Study design and participants

This is an observational study to evaluate the degree of transmissibility of SARS-CoV-2 variants, as demonstrated by the positive rate in detecting COVID-19 cases in HRRBs undergoing RTD, as well as the presence of suspected vertical transmission. Diagnosis of COVID-19 is confirmed by reverse transcription polymerase chain reaction (RT-PCR) using combined nasal and throat swabs collected by staff with training. Deep throat saliva was accepted as an alternative specimen [30]. Whole-genome sequencing was performed directly on the above-mentioned specimens from laboratory-confirmed COVID-19 cases. This study was approved by the Institutional Review Board of The University of Hong Kong/Hospital Authority Hong Kong West Hospital Cluster.

2.5. SARS-CoV-2 Pangolin lineage information

Viral genomes and the Pangolin lineage designations were obtained

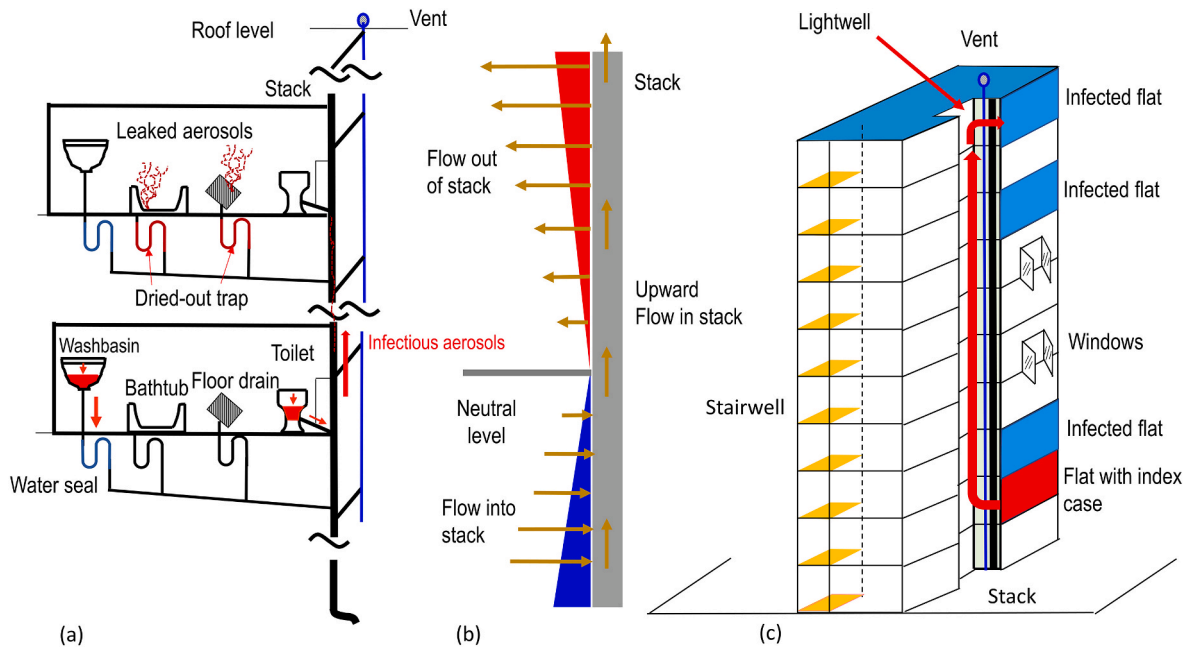


Fig. 1. Schematic representation of vertical transmission of SARS-CoV-2 in high-rise residential buildings.

Note: (a) Backflow of infectious aerosols (from vertical drainage stack) to indoor environment via dried out U-trap (red). The aerosols (red dots) can be generated during discharge of wastewater from a water basin or toilet from flat beneath (red), and such aerosols ascend through vertical stack and can leak back into bathrooms of an upper flat via dried out U-trap. (b) Chimney effect driving air through the vertical drainage stack from low temperature (blue) to high temperature (red). The chimney effect within the stack causing upward air flow will lead to a relatively negative pressure at the lower part of the drainage stack (blue), therefore drawing air in through leaks. The warm air rises through the stack, and the relative positive pressure (red) in the upper part can result in the outflow of contaminated stack aerosol into the bathrooms through leaks of drainage pipes. Generally the top floors have a higher temperature due to sunshine than the lower floors which promotes an upward air flow in stack. (c) Usual pattern of vertical transmission (ascending) of COVID-19 potentially through vertical drainage stack of lightwell. The commonly observed spatial pattern of infected recipient flats (in blue) against an index flat (in red) (which can be the lower or upper flats). The non-infected flats are shown in white. Other suspected transmission mechanisms include flows by chimney effect in the stairwell and the lightwell with façade plumes from re-entry circuit created by open windows and extraction fans facing the lightwell. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

from the GISAID database. We included viral genomes that we have published previously [17,32].

2.6. Statistical analysis

Difference in the positive rates of SARS-CoV-2 among residents and flats in HRRBs across the fourth and fifth waves of COVID-19 was analyzed using Chi-square test or Fisher exact test for categorical variables. A two-sided p -value of <0.05 was considered statistically significant.

3. Results

3.1. Epidemiology of COVID-19 in Hong Kong

Before the start of the fifth wave, a total of 12,636 confirmed COVID-19 cases were reported in Hong Kong with an incidence of 1685 cases per million population. There were 6103 (48.3%) males. The median age was 43 years (range: 12 days to 100 years). The epidemiological information of COVID-19 outbreaks from the first to fourth waves is shown in Appendix 1 to 4. The fifth wave started with two infected air crew members who transmitted the Omicron variant to another 68 cases since late December 2021 (Fig. 2a and b), among which eight secondary cases were associated with an outbreak in a Chinese restaurant [31]. Subsequently, another outbreak due to imported hamsters with probable hamster-to-human transmission of Delta variant in pet shops led to 84 cases since 17 January 2022 (day 749) (Table 1), the first 58 cases of which has been reported previously [32,33]. Finally, another outbreak of SARS-CoV-2 Omicron subvariant BA.2 started with a case who acquired the infection in a designated quarantine hotel for inbound

travelers and subsequently spread into the community since 9 January 2022 (day 741). This BA.2 subvariant became the dominant strain leading to an explosive outbreak at a public housing estate, the Kwai Chung Estate since 21 January 2022 (day 753). The epidemiological information of the first 432 cases related to this outbreak was reported previously [17].

3.2. Restriction-testing declaration for residents in high-rise residential buildings

From 23 January 2021 (day 390) to 24 March 2022 (day 815), a total of 436,397 residents from 354 HRRBs were tested for SARS-CoV-2, of which 25,450 (5.8%) residents from 223 (63.0%) HRRBs tested positive. Excluding 22,801 residents from 38 HRRBs tested negative outside the 12-week periods selected in fourth and fifth waves, respectively, the rate of COVID-19 detection was significantly higher during the fifth wave than the fourth wave (6.5%, 25,434/389,700 vs 0.07%, 16/23,896; $p < 0.001$) (Table 2). Similarly, the proportion of HRRBs with COVID-19 cases under RTD was also significantly higher during the corresponding periods of comparison (78.2%, 219/280 in the fifth wave vs 11.1%, 4/36 in the fourth wave; $p < 0.001$). Public HRRBs constituted 58.2% (206/354) of all HRRBs under RTD, and the proportion of public HRRBs under RTD progressively increased during the fifth wave (Fig. 3). The proportion of public HRRBs under RTD was significantly higher during the fifth wave than the fourth wave (70.7%, 198/280 vs 8.3%, 3/36, $p < 0.001$).

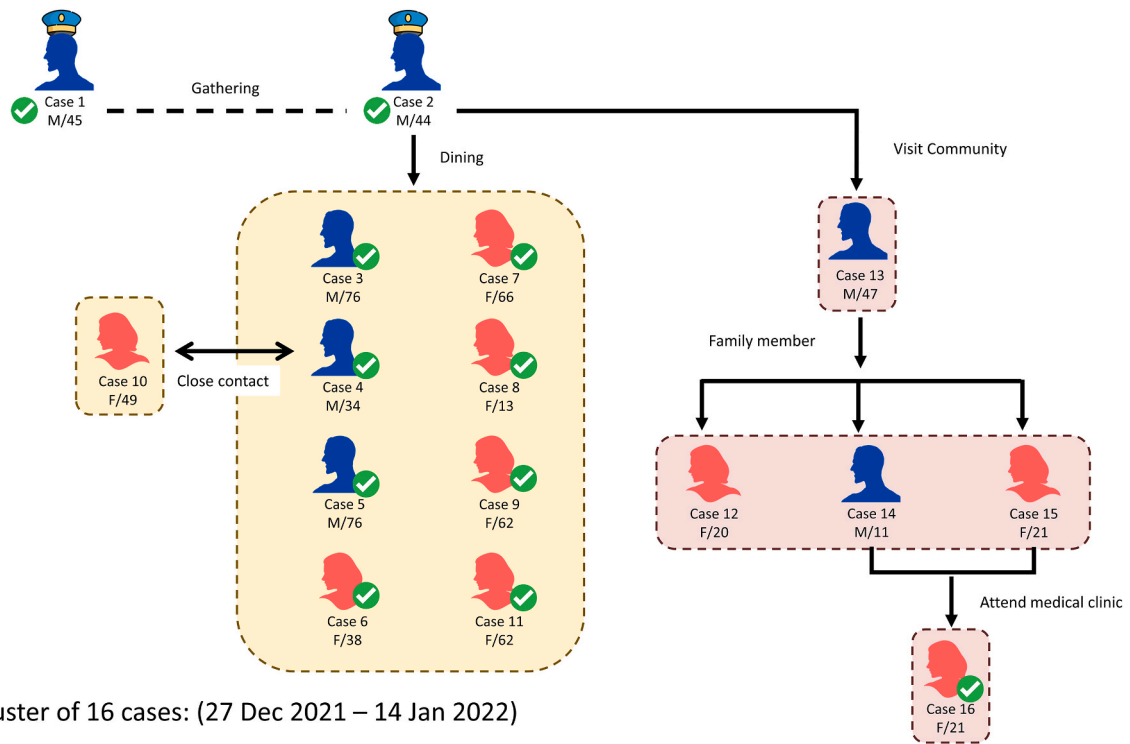


Fig. 2a. Schematic representation of community transmission of a cluster of 16 cases infected with the Omicron variant transmitted from an infected air crew member. Note. Case 2 was the index case in this outbreak. Case 3 to 9 and case 11 belonged to an outbreak in a Chinese restaurant which was recently reported [31]. The “tick” symbol represents completion of two doses of COVID-19 vaccination.

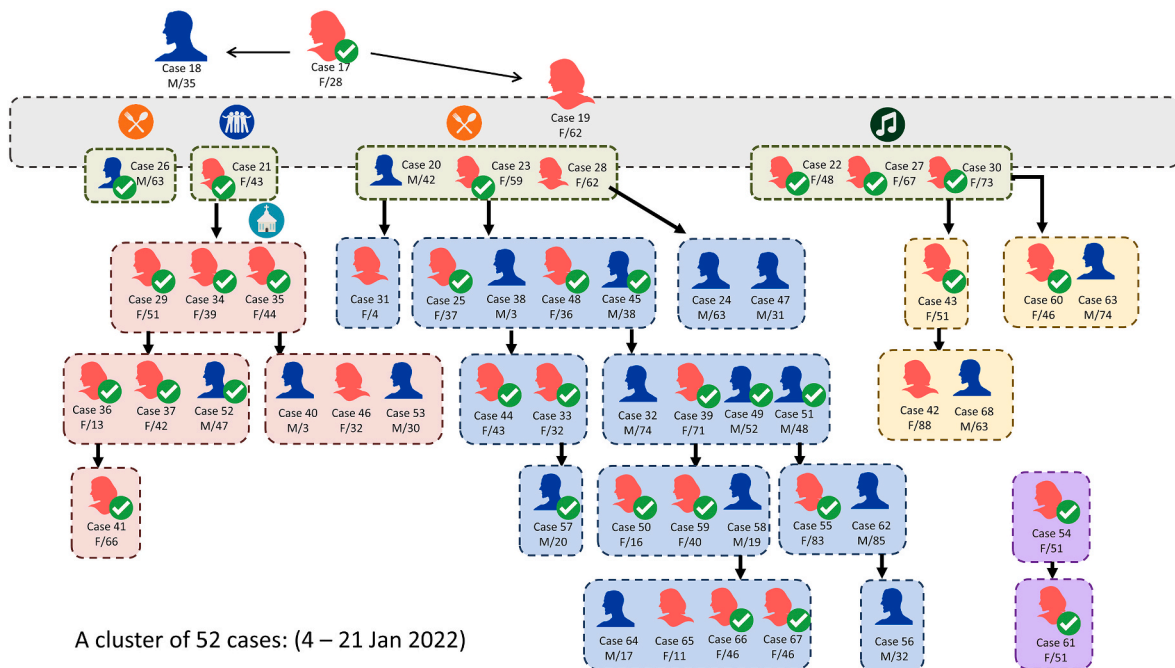


Fig. 2b. Schematic representation of community transmission of a cluster of 52 patients infected with the Omicron variant transmitted from an infected air crew member. Note. Case 17 was the index case in this outbreak. Case 19, which was a household contact, acquired SARS-CoV-2 and further spread the infection in the community. The “tick” symbol represents completion of two doses of COVID-19 vaccination.

3.3. Suspected vertical transmission of COVID-19 in high-rise residential buildings

During the fourth wave of COVID-19 and after the implementation of RTD, four HRRBs with COVID-19 positive cases were reported, and all

had detailed residential addresses for analysis. A total of 16 COVID-19 cases were identified from ten (0.79%) of 1272 flats, and six residents from three (0.24%) flats were involved in vertical transmission of COVID-19 during our on-site investigation [14]. During the fifth wave, the residential addresses of newly diagnosed COVID-19 cases were

Table 1

Summary of COVID-19 outbreaks involving more than 10 cases during the fifth wave of COVID-19 in Hong Kong.

No.	Wave of COVID-19	Name of outbreak	Nature of outbreak	Duration (days) of outbreak	No. of cases (M/F)	Median age, yrs (range)	Symptomatic (%)	Remark [SARS-CoV-2 variant]
5.1	5th	Air crew (12611) related	Dining related	28 Dec 2021–14 Jan 2022 (18)	16 (6/10)	45 (11–76)	14 (87.5%)	Imported case (2); linked with imported case (14) [Omicron variant]
5.2	5th	Air crew (12676) related	Recreation related	2 Jan – 21 Jan 2022 (20)	52 (20/32)	46 (3–88)	44 (84.6%)	Imported case (1); linked with imported case (51) [Omicron variant]
5.3	5th	Hamster-related cluster ^a	Recreation related	17 Jan – 5 Feb 2022 (20)	84 (41/43)	51 (1–96)	58 (69.0%)	Local case (1); linked with local case (83) [Delta variant]
5.4	5th	Silka Seaview Hotel ^b	Explosive	8 Jan - 5 Feb 2022 (29) ^c	768 (374/394)	41 (1mo-90)	298 (38.8%)	Imported case (2); linked with imported case (766) [Omicron subvariant BA.2]

^a The epidemiological information of the first 58 cases was reported previously [32,33].

^b The epidemiological information of the 432 residents, visitors or staff related to the outbreak in a single housing estate (Kwai Chung Estate) was reported previously [17].

^c The epidemiological information of the individual case was no longer listed out in the website of Centre for Health Protection after 6 February 2022.

Table 2Summary of high-rise residential buildings (HRRBs) undergoing restriction-testing declaration (RTD) during the fourth and fifth waves of COVID-19 epidemic in Hong Kong^a.

	Selected 12-week period during the fourth wave ^b	Selected 12-week period during the fifth wave (Omicron variant) ^c	P value
Calendar date	28 Jan to 21 Apr 2021	31 Dec 2021 to 24 Mar 2022	
Day of COVID-19 combat (duration, day)	395 to 478 (84)	732 to 815 (84)	
Number of HRRB undergoing RTD	36	280	
Private HRRB	33/36 (91.7%)	82/280 (29.3%)	<0.001
Public HRRB	3/36 (8.3%)	198/280 (70.7%)	<0.001
Number (%) of HRRB with positive case	4/36 (11.1%)	219 (78.2%)	<0.001
Median number (range) of case per HRRB	NA	86 (1–382)	
Median percentage (range) of case per HRRB	NA	8.7% (0.1%–30.9%)	
Number of HRRB under RTD per day	0.43	2.6	<0.001
Number of residents tested	23,896	389,700	
Number of residents positive for SARS-CoV-2	16	25,434	
Positive rate for SARS-CoV-2 among residents	0.07%	6.5%	<0.001
Number of flats with COVID-19 patients	10	6766	
Number (%) of vertically aligned flats with COVID-19 patients	3 (30.0%)	6471 (95.6%)	<0.001

^a Under the restriction-testing declaration (RTD), personal movement in the concerned premises was restricted until all persons were tested for SARS-CoV-2 in the on-site mobile testing center arranged by the government. The result of RTD was analyzed until 24 March 2022, day 815 of combat of COVID-19 in Hong Kong.

^b A comparable 12-week period chosen in the fourth wave included all HRRBs under the scheme of RTD except for two HRRBs with a total of 1900 residents who were tested negative for SARS-CoV-2 on 23 April 2021 and 29 April 2021.

^c Predominantly caused by SARS-CoV-2 Omicron variant and gradually replaced by Omicron subvariant BA.2 since the community outbreak at Kwai Chung Estate on 21 January 2022 (day 753).

available for 73 (26.1%) of 280 HRRBs under the scheme of RTD between 6 February 2022 and 18 March 2022. Within these 73 HRRBs, 6766 (14.9%) of 45,531 flats had 10,364 newly diagnosed COVID-19 cases. Among these 45,531 flats, 6471 (14.2%) were suspected to have vertical transmission. A significantly higher percentage of residential flats were involved in suspected vertical transmission of COVID-19 during the fifth than the fourth wave (14.2%, 6471/45,531 vs 0.24%, 3/1272; $p < 0.001$). Given a total number of residential flats of 2,924,000 in Hong Kong [34], the proportion of flats involved in suspected vertical transmission was significantly higher in the fifth wave than in the fourth wave (2212 vs 1 per million residential flats, $p < 0.001$). Within the flats with COVID-19 cases, the proportion of vertically aligned flats was also significantly higher in the fifth wave than in the fourth wave (95.6%, 6471/6766 vs 30.0%, 3/10, $p < 0.001$).

The number of COVID-19 cases living in the flats involved in suspected vertical transmission was significantly higher in the fifth wave compared with the fourth wave (95.4%, 9885/10,364 vs 37.5%, 6/16; $p < 0.001$). Given the total number of COVID-19 cases during the 12-week comparison period in fourth wave (1422 cases) and fifth wave (1,088,593 cases), the contribution of suspected vertical transmission to the total number of COVID-19 cases was significantly higher in the fifth waves compared with the fourth wave (0.91%, 9885/1,088,593 vs 0.42%, 6/1422; $p < 0.05$).

During the fifth wave, the percentage of flats with infected cases was significantly higher in public HRRBs than in private HRRBs (15.2%, 6516/42,880 vs 9.4%, 250/2651; $p < 0.001$). As shown in Fig. 4, both the percentage of residents tested positive and the percentage of flats involved in suspected vertical transmission were increasing with the expansion of the epidemic from February to March 2022. The detailed information of these 73 HRRBs is summarized in Appendix 5.

3.4. Whole-genome phylogenetic analysis

Whole-genome phylogenetic analysis of 332 SARS-CoV-2 genomes collected from both affected residents from HRRBs (121 strains) and other infected persons (211 strains) from January 2022 showed that Omicron subvariant BA.2 was the predominant virus in the fifth wave (Supplementary Figure).

4. Discussion

In Hong Kong, the fifth wave of COVID-19 began on 31 December 2021, at the start of the third year since the official announcement of outbreak of community acquired pneumonia in Wuhan, Hubei Province, China. Similar to the global epidemiology of COVID-19, our fifth wave was predominantly driven by the Omicron variant, which has resulted in an explosive outbreak in Southern Africa [35]. Due to the huge number of cases, we were unable to perform contact tracing to know whether the

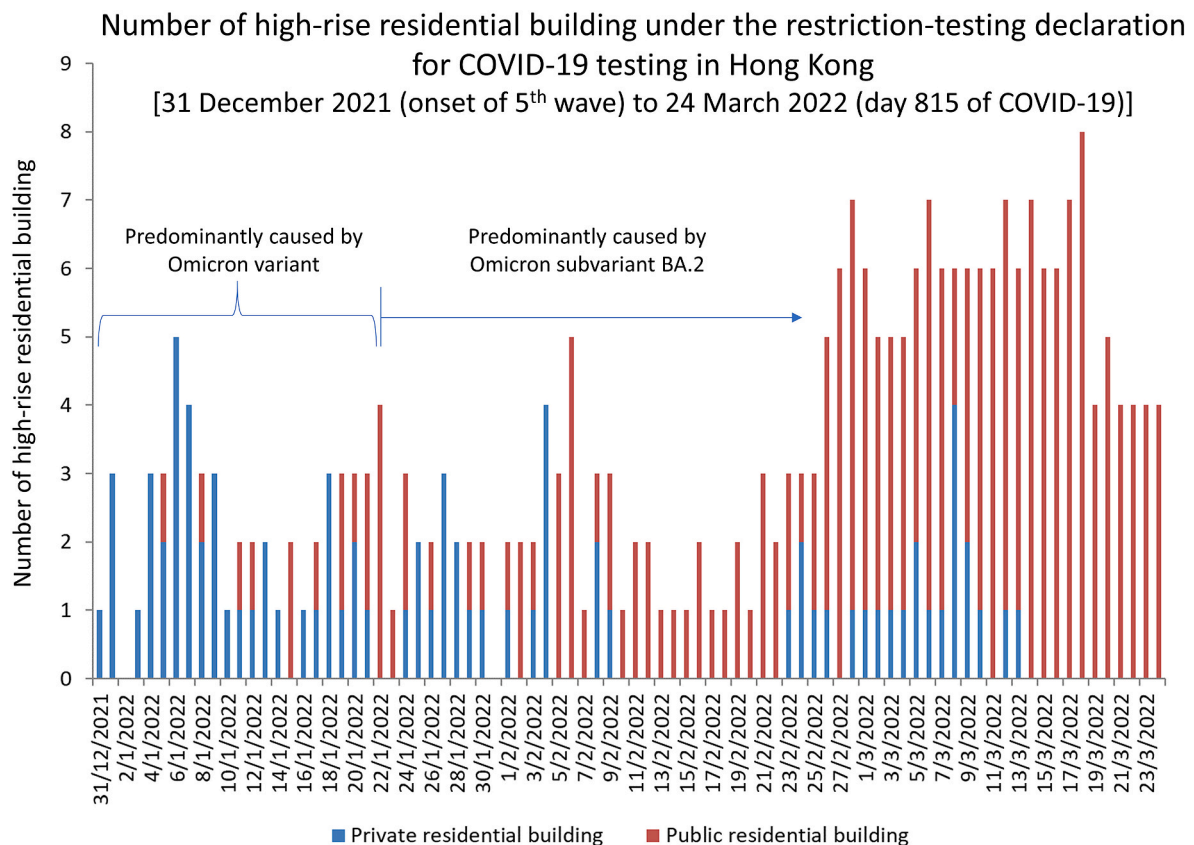


Fig. 3. Number of residential buildings under restriction-testing declaration for COVID-19 testing in Hong Kong.

cases originated from catering premise, recreational areas, workplace, schools, or wet markets as we did in the first to fourth wave (Appendix 1 to 4). Nevertheless, targeted COVID-19 screening for people living in HRRBs under the scheme of RTD was maintained during the fifth wave. The positive rate among residents in these HRRBs was 93 times higher than that in the fourth wave, during which the predominant viral strain was B.1.36.27. In addition, the number of HRRBs with newly diagnosed COVID-19 cases under RTD was 55 times higher than that in the fourth wave.

The clustering of COVID-19 cases in HRRBs is rather unique in Hong Kong, where the population density was 7126 persons per square kilometer, among the top four in the world [36]. However, it is difficult to delineate the mode of transmission within HRRBs as the residents may get into contact with each other directly or indirectly in the communal area of the buildings, or acquire the infection from their household members. Therefore, we further analyzed the mode of transmission using the location of the residential flat of each family unit to demonstrate the increased transmissibility of SARS-CoV-2 Omicron variant by airborne route.

The mechanism of SARS-CoV-2 transmission in HRRBs has been investigated before the beginning of the fifth wave [14,15]. Aerosol transmission of SARS-CoV-2 was demonstrated by injecting tracer gas into the drainage stacks via the water closet of the index case, and measuring tracer gas concentrations in the bathrooms and along the facades of infected and non-infected flats and on the rooftop. We showed that the aerosol in the stacks can spread indoor through pipe leaks due to chimney effect, which provided direct evidence for long-range aerosol transmission of SARS-CoV-2 through drainage pipes [14]. Probable aerosol transmission of SARS-CoV-2 was previously reported in one of our housing estates in during the 2003 outbreak of SARS [13], and also suggested by an outbreak affecting three vertically aligned flats connected by drainage pipes in the master bathrooms in an HRRB in

Guangzhou, China [37]. Similarly, clustering of infected cases was found among two vertically aligned flats on different floors of an apartment building, where each flat was connected through a single air duct in the bathroom for natural ventilation in Seoul, South Korea [38]. In addition, aerosol transmission of SARS-CoV-2 possibly occurred between different floors of an apartment building aligned in the same direction via nonfunctioning drain traps [39]. Therefore, the number of vertically aligned flats involved in suspected vertical transmission of COVID-19 in HRRBs appears to be a reasonable surrogate marker to assess the airborne transmission potential of SARS-CoV-2 throughout the evolution of the pandemic.

With the emergence of the Omicron variant in the fifth wave of COVID-19 outbreak in Hong Kong, the number of vertically aligned flats involved in suspected vertical transmission was more than 2000 times higher than that in the fourth wave. This finding may be due to the high average basic and effective reproduction numbers of 8.2 and 3.6, respectively, for the Omicron variants [40], with the subvariant BA.2 being even more contagious than BA.1 [12]. Our whole-genome analysis also demonstrated the predominance of Omicron subvariant BA.2 since January 2022 in Hong Kong.

Vertical transmission of SARS-CoV-2 may be an important cause of airborne transmission in densely populated HRRBs in Hong Kong. Before the fifth wave, all residents from HRRBs implicated in transmission chains were evacuated to quarantine centers to reduce the risk of further transmission. When the highly transmissible Omicron variant in the fifth wave has affected 8.7% of the residents per HRRB which overwhelmed the quarantine facilities, it was no longer possible to isolate and quarantine all the residents. Flats in public HRRBs constituted almost 97% of all vertically aligned flats involved in suspected vertical transmission. Around half of the Hong Kong population live in public HRRBs, which are provided by the Hong Kong Government to subsidized populations and people of lower socioeconomic status, who are at higher risk of

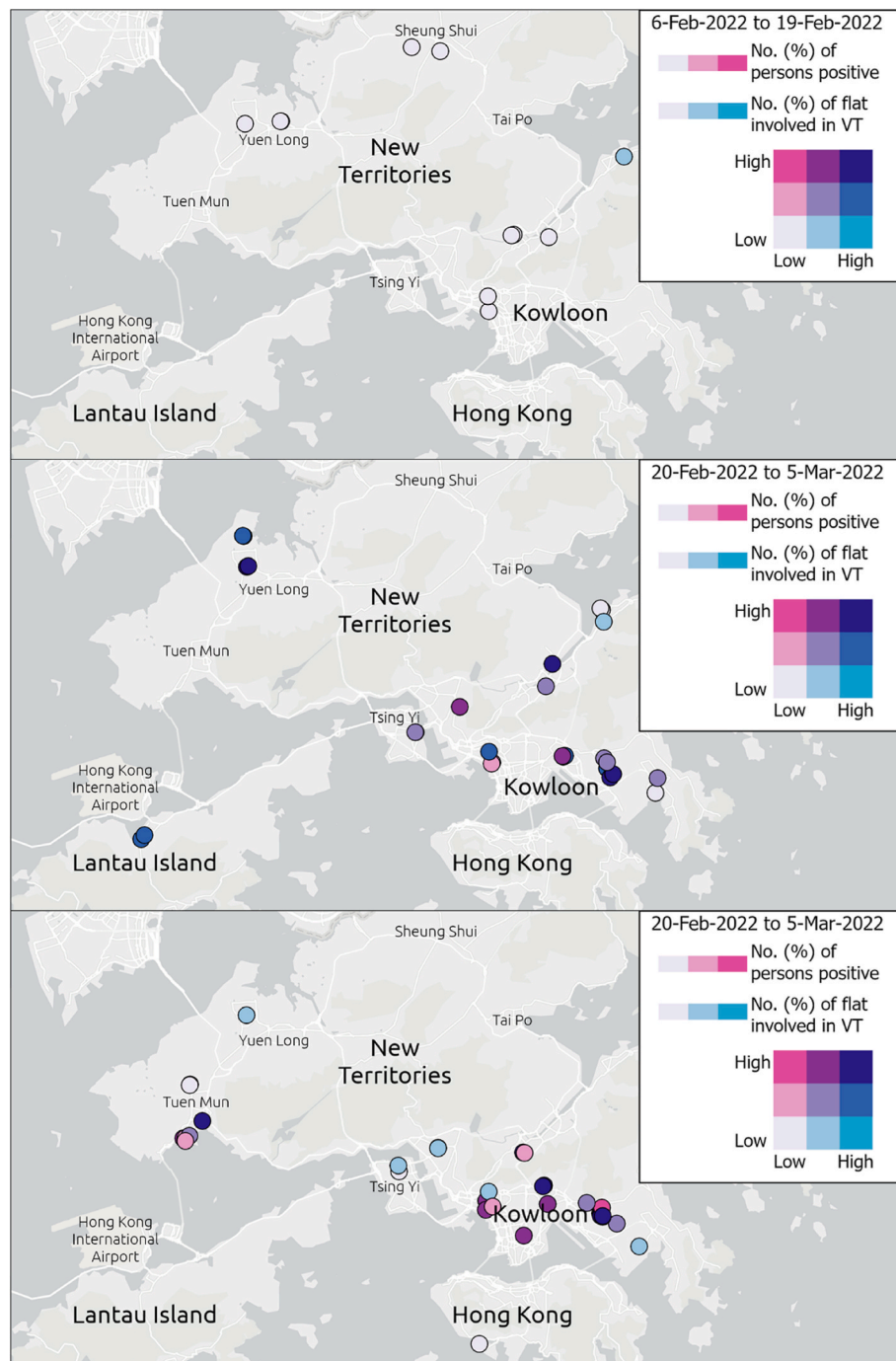


Fig. 4. The geographic distribution of 73 high-rise residential buildings (HRRBs) under the scheme of restriction-testing declaration (RTD) between 6 February 2022 and 18 March 2022. This map is symbiosed by 3×3 bivariate colors. The quantile classification is based on (i) the percentage of persons positive and (ii) percent of flat involved in vertical transmission (VT) among the HRRBs.

acquiring COVID-19 [41]. The sharp difference in observed transmission between the public and private residential buildings is interesting. The public buildings have generally smaller areas per flat, larger number of persons per room, more flats on each floor, and much larger number of persons per block than private buildings [42]. Overcrowding is known to be associated with increased risk of transmission of respiratory infection among residents. How overcrowding and vertical or horizontal transmission interact in public residential buildings remains to be studied. While the architectural and engineering design of public HRRBs in relation to the risk of airborne transmission of respiratory viruses requires further investigation, vertical transmission of SARS-CoV-2 in

these HRRBs could be one of the factors driving the uncontrolled fifth wave of community outbreak in Hong Kong. In term of vertical transmission, the building drainage systems are generally better managed in private housing than in public housing in Hong Kong. There have also been reports that unauthorized alterations were made to some building drainage pipes in some public housing [43]. Aging public housing has been known in Hong Kong [44]. If one takes airborne transmission as the predominant route, one may argue that one type of over-crowding (i.e. smaller floor area per person) effectively means poor ventilation in public housing. Poor ventilation effectively enhances secondary or tertiary transmission.

If further studies can be performed to confirm our hypothesis that vertical transmission in HRRBs have contributed significantly during the fifth wave of COVID-19 outbreak in Hong Kong, the need for investigating the exact cause of such vertical transmission and adopting mitigation measures is obvious. Similar vertical transmission related outbreaks have not been widely reported in other cities except Guangzhou [37]. It has been well known that air pressure variation exists in building drainage systems during wastewater discharge [45]. Studies prior to the COVID-19 pandemic have suggested the possible roles of such air pressure variation in the spread of infection [46,47]. Furthermore, the possible role of chimney effect adds to the need for studying air flows and foul gas control within drainage pipes in high-rise buildings [14,15]. During the current pandemic, we recommend residents to regularly fill U-traps in bathrooms and kitchen with water, and regularly check their drainage systems for air tightness [14,15].

There are several limitations in this study. First, it is not possible to perform detailed epidemiological analysis for each HRRB with suspected vertical transmission in the fifth wave. We can only refer to our previous experience during on-site investigations for COVID-19 outbreaks in HRRBs. Novel mechanism of transmission of SARS-CoV-2 by airborne route and/or other routes in relation to the architectural and engineering design in HRRBs may have been missed. Second, misclassification of a person who may have acquired the SARS-CoV-2 from the community other than from the HRRBs is possible. The COVID-19 positive case may just be detected during compulsory COVID-19 testing under the RTD. Since this potential bias or uncertainty may occur during both the fourth and fifth wave of COVID-19 in Hong Kong, such occurrence may reduce the risk of bias in comparing the number and rate of COVID-19 case diagnosed during compulsory COVID-19 testing in the HRRBs. Third, it was not possible to determine the exact number of residents who have definitely acquired the infection via vertical transmission instead of other routes of transmission which may occur within the same household. Therefore, we only used the number of vertically aligned flats with shared drainage stack and lightwell as a surrogate marker of suspected vertical transmission. However, the number of flats involved in airborne transmission may be underestimated. Since various types of drainage stack systems may exist in HRRBs, previous and the present studies are only limited to certain number of specific systems [14–16]. Apart from vertical transmission resulting from aerosols leakage through drainage stacks, horizontal transmission through airflow across the hallway has been demonstrated in our previous investigation [15]. Furthermore, the path of airflow in the corridor and re-entry airflow to other flats may contribute to the airborne transmission of SARS-CoV-2 in the HRRBs [48]. Nevertheless, the highly significant increase in the number of flats with suspected vertical transmission of SARS-CoV-2 during the fifth wave indicates the markedly higher potential for airborne transmission of Omicron variant. In summary, our findings suggested that the high transmissibility of Omicron variant BA.2 strain has likely exploited the unique mechanism of vertical transmission in HRRBs of Hong Kong which has at least partially contributed to this explosive outbreak through drainage pipes and lightwells by airborne excreta-aerosol particles. This outbreak of our fifth wave has completely overwhelmed the

epidemiological measures of stringent border control, widespread daily testing of the symptomatic, contacts and at-risk workers, case isolation and contact quarantine, universal masking, work from home, and closure of schools and public premises which were proven to have been successful in the first two years of pandemic before the Omicron variant comes. The fifth wave has finally infected over one million of our population with over 9000 deaths [19].

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CRediT authorship contribution statement

Vincent Chi-Chung Cheng: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Shuk-Ching Wong:** Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Albert Ka-Wing Au:** Investigation, Resources. **Cheng Zhang:** Resources. **Jonathan Hon-Kwan Chen:** Data curation. **Simon Yung-Chun So:** Data curation. **Xin Li:** Writing – review & editing. **Qun Wang:** Resources. **Kelvin Keru Lu:** Investigation. **David Christopher Lung:** Investigation, Resources. **Vivien Wai-Man Chuang:** Resources. **Eric Schuldenfrei:** Resources. **Gilman Kit-Hang Siu:** Investigation, Resources. **Kelvin Kai-Wang To:** Investigation, Resources. **Yuguo Li:** Conceptualization, Formal analysis, Project administration, Supervision, Methodology, Writing – review & editing. **Kwok-Yung Yuen:** Conceptualization, Formal analysis, Funding acquisition, Project administration, Supervision, Methodology, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.buildenv.2022.109323>.

Appendix 1. Summary of COVID-19 outbreaks involving more than 10 cases during the first wave of COVID-19 in Hong Kong

No.	Wave of COVID-19	Name of outbreak	Nature of outbreak	Duration (days) of outbreak	No. of cases (M/F)	Median age, yrs (range)	Symptomatic (%)	Remark [mortality number, %, if any]
1.1	1st	Diamond Princess Cruise Ship			11 (5/6)	58 (16–80)	7 (63.6%)	Imported cases (11)

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No.	Wave of COVID-19	Name of outbreak	Nature of outbreak	Duration (days) of outbreak	No. of cases (M/F)	Median age, yrs (range)	Symptomatic (%)	Remark [mortality number, %, if any]
1.2	1st	Hotpot dinner gathering at Kwun Tong Fook Wai Ching She in Maylun Apartments in North Point	Travel related	1 Feb – 1 Mar 2020 (30)	13 (6/7)	51 (22–91)	13 (100%)	Local case (1); linked with local case (12)
1.3	1st		Dining related	9 Feb – 12 Feb 2020 (4)				
1.4	1st	Travel tour to Egypt	Worship related	19 Feb – 8 Mar 2020 (19)	19 (6/13)	68 (24–96)	15 (78.9%)	Possibly local case (1); linked with possibly local case (18) [1, 5.3%]
	1st		Travel related	10 Mar – 14 Mar 2020 (5)				
	Subtotal			1 Feb – 14 Mar 2020 (43)	53 (23/30)	57 (16–96)	45 (84.9%)	Imported cases (20, 44.4%) [1, 1.9%]

Appendix 2. Summary of COVID-19 outbreaks involving more than 10 cases during the second wave of COVID-19 in Hong Kong

No.	Wave of COVID-19	Name of outbreak	Nature of outbreak	Duration (days) of outbreak	No. of cases (M/F)	Median age, yrs (range)	Symptomatic (%)	Remark [mortality number, %, if any]
2.1	2nd	Bar and band cluster	Dining related	18 Mar – 13 Apr 2022 (27)	103 (56/47)	37 (1m-77)	87 (84.5%)	Local case (1); linked with local case (102)
2.2	2nd	Wedding party at Lantau Island	Dining related	18 Mar – 24 Mar 2020 (7)	15 (7/8)	32 (1–69)	13 (86.7%)	Possibly local case (1); linked with possibly local case (14)
2.3	2nd	Kerry Logistics	Workplace related	31 May – 13 Jun 2020 (14)	12 (4/8)	56 (27–78)	100 (100%)	Local case (1); linked with local case (11) [2, 16.7%]
	Subtotal			18 Mar – 13 Jun 2022 (88)	130 (67/63)	38 (1m-78)	112 (86.2%)	Imported case (0, 0%) [2, 1.5%]

Appendix 3. Summary of COVID-19 outbreaks involving more than 10 cases during the third wave of COVID-19 in Hong Kong

No.	Wave of COVID-19	Name of outbreak	Nature of outbreak	Duration (days) of outbreak	No. of cases (M/F)	Median age, yrs (range)	Symptomatic (%)	Remark [mortality number, %, if any]
3.1	3rd	Bun Kee/Sun Fat/Kin Wing	Dining related	5 Jul – 30 Jul 2020 (26)	46 (29/17)	59 (8–74)	40 (87.0%)	Local case (2); linked with local case (44)
3.2	3rd	Kong Tai Care for the Aged Centre	RCHE related	7 Jul – 7 Aug 2020 (32)	46 (31/15)	72 (18–95)	23 (50.0%)	Local case (1); linked with local case (45) [9, 19.6%]
3.3	3rd	Ming Chuen House of Shui Chuen O Estate	Residential building	7 Jul – 10 Jul 2020 (4)	12 (2/10)	32 (7–89)	4 (33.3%)	Local case (1); linked with local case (11)
3.4	3rd	Tsz Wan Shan Shopping Centre Green River	Dining related	11 Jul – 27 Jul 2020 (17)	37 (18/19)	51 (2–90)	32 (86.5%)	Local case (2); linked with local case (35)
3.5	3rd	Tsz Wan Shan Shopping Centre Windsor	Dining related	13 Jul – 19 Jul 2020 (7)	22 (10/12)	44 (4–73)	20 (90.9%)	Local case (1); linked with local case (21)
3.6	3rd	Tsz Wan Shan Shopping Centre Deluxe Cuisine	Dining related	9 Jul – 27 Jul 2020 (19)	24 (11/23)	60 (2–94)	21 (87.5%)	Local case (1); linked with local case (23) [3, 12.5%]
3.7	3rd	Grand Plaza Taoheung	Dining related	16 Jul – 14 Aug 2020 (30)	42 (16/26)	56 (14–86)	35 (83.3%)	Local case (2); linked with local case (40)
3.8	3rd	Tuen Mun Central Square Fulum Restaurant	Dining related	18 Jul – 2 Aug 2020 (16)	44 (22/22)	56 (12–81)	40 (90.9%)	Local case (2); linked with local case (42)
3.9	3rd	Metropiazza Chiuchow Garden	Dining related	18 Jul – 8 Aug 2022 (22)	20 (12/8)	57 (6–91)	18 (90.0%)	Local case (2); linked with local case (18)
3.10	3rd	Metropark Hotel Mongkok Victoria Harbour Restaurant	Dining related	13 Jul – 30 Jul 2020 (18)	14 (5/9)	60 (27–70)	13 (92.9%)	Local case (5); linked with local case (9)
3.11	3rd	The Salvation Army Lung Hang Residence For Senior Citizens	RCHE related	22 Jul – 15 Aug 2022 (25)	15 (6/9)	56 (6–100)	9 (60.0%)	Local case (1); linked with local case (14) [3, 20.0%]
3.12	3rd	Cornwall Elderly's Home (Golden Branch), Tuen Mun	RCHE related	24 Jul – 6 Aug 2022 (14)	40 (10/30)	83 (34–96)	36 (90.0%)	Local case (1); linked with local case (39) [11, 27.5%]
3.13	3rd	Millennium City phase 3	Construction site	25 Jul – 4 Aug 2020 (11)	32 (21/11)	38 (2–69)	29 (90.6%)	Local case (2); linked with local case (30)
3.14	3rd	Star Global Direct Sales	Workplace related	24 Jul – 22 Aug 2020 (30)	61 (26/35)	23 (21–64)	52 (85.2%)	Local case (1); linked with local case (60)
3.15		Sheung Shui Slaughter House	Workplace related	27 Jul – 8 Aug 2020 (13)	24 (14/10)	39 (1–71)	19 (79.2%)	Local case (2); linked with local case (22)
3.16	3rd	Construction site at Kong Nga Po, Man Kam To	Construction site	30 Jul – 10 Aug 2020 (12)	23 (13/10)	43 (11–76)	18 (78.3%)	Local case (2); linked with local case (21)
3.17	3rd	Hung Hom Market	Wet market	19 Jul – 5 Aug 2020 (18)	13 (5/8)	59 (24–73)	9 (69.2%)	Local case (1); linked with local case (12)
3.18	3rd	Sham Shui Po King Fok Nursing Home	RCHE related	30 Jul – 8 Aug 2020 (10)	14 (11/3)	73 (47–95)	12 (85.7%)	Local case (1); linked with local case (13) [4, 28.6%]

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No.	Wave of COVID-19	Name of outbreak	Nature of outbreak	Duration (days) of outbreak	No. of cases (M/F)	Median age, yrs (range)	Symptomatic (%)	Remark [mortality number, %, if any]
3.19	3rd	Kwai Tsing Container Terminals	Workplace related	29 Jul – 27 Aug 2020 (30)	76 (64/12)	54 (3–87)	49 (64.5%)	Local case (1); linked with local case (75)
3.20	3rd	Hong Chi Lei Muk Shue Hostel	RCHD related	23 Aug – 3 Sep 2020 (12)	24 (8/16)	41 (18–87)	15 (62.5%)	Local case (1); linked with local case (23)
3.21	3rd	Transport City Building, Tai Wai	Workplace related	2 Sep – 20 Sep 2020 (19)	17 (8/9)	46 (12–64)	12 (70.6%)	Local case (1); linked with local case (16)
3.22	3rd	China Secret/Holly Mansion	Recreational related	1 Oct – 13 Oct 2020 (13)	15 (6/9)	29 (18–82)	11 (73.3%)	Local case (1); linked with local case (14)
3.23	3rd	The Home of Treasure	RCHD related	7 Oct – 21 Oct 2020 (15)	20 (12/8)	56 (25–76)	11 (55.0%)	Local case (1); linked with local case (19)
	Subtotal			5 Jul – 21 Oct 2020 (109)	681 (360/321)	54 (1–100)	528 (77.5%)	Imported case (0, 0%) [30, 4.4%]

RCHD, residential care home for the disability; RCHE, residential care home for the elderly.

Appendix 4. Summary of COVID-19 outbreaks involving more than 10 cases during the fourth wave of COVID-19 in Hong Kong

No.	Wave of COVID-19	Name of outbreak	Nature of outbreak	Duration (days) of outbreak	No. of cases (M/F)	Median age, yrs (range)	Symptomatic (%)	Remark [mortality number, %, if any]
4.1	4th	Dancing/Singing Cluster	Recreation related	19 Nov – 22 Dec 2020 (34)	732 (314/418)	57 (8m-95)	519 (70.9%)	Local case (3); linked with local case (729) [18, 2.5%]
4.2	4th	Sky Cuisine (Sheung Wan)	Dining related	28 Nov – 7 Dec 2020 (10)	22 (9/13)	54 (5–72)	19 (86.4%)	Local case (1); linked with local case (21)
4.3	4th	Tung Wah Group Of Hospitals Fong Shu Chuen Day Activity Centre cum Hostel	Day Centre	29 Nov – 19 Dec 2020 (11)	61 (32/29)	47 (21–74)	22 (36.1%)	Local case (1); linked with local case (60) [1, 1.6%]
4.4	4th	Construction sites at LOHAS Park Kai Tak	Construction site	1 Dec – 19 Dec 2020 (19)	74 (42/32)	44 (2–97)	52 (70.3%)	Local case (5); linked with local case (69)
4.5	4th	Chuen Cheung Kui	Dining related	28 Nov – 4 Dec 2020 (7)	12 (5/7)	53 (17–72)	8 (66.7%)	Local case (1); linked with local case (11)
4.6	4th	Otto e Mezzo 8½ Bombana	Dining related	28 Nov – 19 Dec 2020 (22)	23 (13/10)	33 (5m-68)	20 (87.0%)	Local case (1); linked with local case (22)
4.7	4th	Lee Gardens Three Duckee	Dining related	3 Dec – 16 Dec 2020 (14)	16 (11/5)	50 (24–71)	13 (81.3%)	Local case (2); linked with local case (14)
4.8	4th	AsiaWorld Expo (quarantine centre for elderly)	RCHE related	6 Dec – 16 Dec 2020 (11)	25 (6/19)	41 (3–74)	17 (68.0%)	Local case (1); linked with local case (24)
4.9	4th	YATA Department Store (Shatin)	Recreation related	6 Dec – 24 Dec 2020 (19)	28 (10/18)	41 (15–65)	22 (78.6%)	Local case (1); linked with local case (27)
4.10	4th	Construction Site at Tseung Kwan O Lam Tin Tunnel	Construction site	9 Dec 2020–5 Jan 2021 (28)	29 (23/6)	41 (8–74)	16 (55.2%)	Local case (1); linked with local case (28)
4.11	4th	Fung Nin Building	Residential building	14 Dec – 21 Dec 2020 (8)	14 (2/12)	36 (6m-58)	8 (57.1%)	Local case (1); linked with local case (13)
4.12	4th	Residents of Unit 33/34, Ming Lai House, Choi Wan Estate	Residential building	9 Dec – 21 Dec 2020 (13)	13 (8/5)	47 (1–86)	12 (92.3%)	Local case (1); linked with local case (12)
4.13	4th	Billy Sir Music Classroom	Recreation related	15 Dec – 25 Dec 2020 (11)	16 (5/11)	64 (29–82)	12 (75.0%)	Local case (1); linked with local case (15)
4.14	4th	Glow Salon and Spa	Recreation related	11 Dec – 23 Dec 2020 (13)	17 (9/8)	33 (5–51)	12 (70.6%)	Local case (1); linked with local case (16)
4.15	4th	Eastern Artificial Island of the Hong Kong Zhuhai Macao Bridge	Construction site	10 Dec – 26 Dec 2020 (17)	13 (3/10)	57 (17–67)	8 (61.5%)	Local case (1); linked with local case (12)
4.16	4th	Patient and Staff of United Christian Hospital Ward 2D	Hospital outbreak	24 Dec 2020–1 Jan 2021 (9)	21 (0/21)	72 (20–92)	17 (81.0%)	Local case (1); linked with local case (20) [4, 19.0%]
4.17	4th	Construction Site at Tseung Kwan O Lam Tin Tunnel (second cluster)	Construction site	3 Jan – 22 Jan 2021 (20)	50 (34/16)	42 (2m-64)	23 (46.0%)	Local case (1); linked with local case (49)
4.18	4th	Cluster related to Central Kowloon Route (Central Tunnel)	Construction site	8 Jan – 19 Jan 2021 (12)	37 (19/18)	34 (1–75)	19 (51.4%)	Local case (2); linked with local case (35)
4.19	4th	Residents of Unit 09, Yan Shek House, Shek Yam Estate	Residential building	12 Jan – 18 Jan 2021 (7)	10 (4/6)	42 (21–78)	8 (80.0%)	Local case (1); linked with local case (9) [1, 10%]
4.20	4th	Restaurant in Hung Hom	Dining related	24 Jan – 28 Jan 2021 (5)	10 (5/5)	31 (25–55)	5 (50.0%)	Local case (1); linked with local case (9)
4.21	4th	Construction site at Hong Kong International Airport Third Runway	Construction site	22 Jan – 21 Feb 2021 (31)	33 (23/10)	36 (14d-54)	18 (54.5%)	Local case (2); linked with local case (31)
4.22	4th	Caritas Lok Yi School	School related	19 Feb – 28 Feb 2021 (10)	12 (6/6)	29 (10–85)	11 (91.7%)	Local case (1); linked with local case (11)
4.23	4th	K11 Musea Mr. Ming's Chinese Dining/Coast Seafood & Grill (Causeway)	Dining related	24 Feb – 10 Mar 2021 (15)	57 (27/30)	44 (1–74)	42 (73.7%)	Local case (1); linked with local case (56)
4.24	4th	URSUS Fitness (Sai Ying Pun)				33 (1–65)	88 (56.8%)	

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No.	Wave of COVID-19	Name of outbreak	Nature of outbreak	Duration (days) of outbreak	No. of cases (M/F)	Median age, yrs (range)	Symptomatic (%)	Remark [mortality number, %, if any]
	Subtotal		Recreation related	10 Mar – 26 Mar 2021 (17) 19 Nov – 26 Mar 2020 (128)	155 (83/72) 1480 (693/787)	48 (14d-97)	991 (67.0%)	Local case (1); linked with local case (154) Imported case (0, 0%) [24, 1.6%]

Appendix 5. Vertical transmission of SARS-CoV-2 Omicron BA.2 detected by restriction-testing declaration (RTD) during the fifth wave of COVID-19 in Hong Kong

No.	Name of building (Administrative district)	Date of RTD	No. of persons tested	No. (%) of persons positive	No. of flats in the building	No. (%) of flats with positive cases ^a	No. (%) of flats involved in VT ^c	No. of units with positive cases ^b	No. (%) of units involved in VT ^c	Website from HKSAR
1	Mei Chi House, Mei Tin Estate (Sha Tin) ^d	6 Feb 2022	4000	15 (0.4%)	800	10/800 (1.3%)	4/10 (40.0%)	7	1/7 (14.3%)	https://www.info.gov.hk/gia/gener al/202202/08/P2 022020800149.htm? fontSize=1
2	Mei King House, Mei Tin Estate (Sha Tin) ^d	6 Feb 2022	4040	13 (0.3%)	760	8/760 (1.1%)	4/8 (50.0%)	6	2/6 (33.3%)	https://www.info.gov.hk/gia/gener al/202202/08/P2 022020800264.htm? fontSize=1
3	Fu Yuet House, Fu Cheong Estate (Sham Shui Po) ^d	7 Feb 2022	4820	29 (0.6%)	746	16/746 (2.1%)	8/16 (50.0%)	11	3/11 (27.3%)	https://www.info.gov.hk/gia/gener al/202202/09/P2 022020900133.htm? fontSize=1
4	Shing Yin House, Tin Shing Court (Tin Shui Wai) ^e	9 Feb 2022	1780	10 (0.6%)	600	3/600 (0.5%)	2/3 (66.7%)	2	1/2 (50%)	https://www.info.gov.hk/gia/gener al/202202/10/P2 022021000421.htm? fontSize=1
5	Fung Ping House, Long Ping Estate (Yuen Long) ^d	9 Feb 2022	890	7 (0.8%)	375	6/375 (1.6%)	0/6 (0%)	6	0/6 (0%)	https://www.info.gov.hk/gia/gener al/202202/10/P2 022021000375.htm? fontSize=1
6	Cheuk Ping House, Long Ping Estate (Yuen Long) ^d	9 Feb 2022	980	7 (0.7%)	405	4/405 (1.0%)	2/4 (50%)	3	1/3 (33.3%)	https://www.info.gov.hk/gia/gener al/202202/10/P2 022021000353.htm? fontSize=1
7	Begonia House, So Uk Estate (Sham Shui Po) ^d	11 Feb 2022	1100	9 (0.8%)	377	7/377 (1.9%)	2/7 (28.6%)	6	1/6 (16.7%)	https://www.info.gov.hk/gia/gener al/202202/12/P2 022021200200.htm? fontSize=1
8	Un Shing House, Un Chau Estate (Sham Shui Po) ^d	11 Feb 2022	1980	23 (1.2%)	799	16/799 (2.0%)	8/16 (50.0%)	11	3/11 (27.3%)	https://www.info.gov.hk/gia/gener al/202202/12/P2 022021200339.htm? fontSize=1
9	Lee Shing House, Lee On Estate (Ma On Shan) ^d	13 Feb 2022	3720	48 (1.3%)	638	28/638 (4.4%)	27/28 (96.4%)	8	7/8 (87.5%)	https://www.info.gov.hk/gia/gener al/202202/15/P2 022021500353.htm? fontSize=1
10	Ching Long House, Ching Ho Estate (Sheung Shui) ^d	15 Feb 2022	3410	48 (1.4%)	799	23/799 (2.9%)	11/23 (47.8%)	14	2/14 (14.3%)	https://www.info.gov.hk/gia/gener al/202202/17/P2 022021700278.htm? fontSize=1
11	Pok Tat House, Pok Hong Estate (Sha Tin) ^d	19 Feb 2022	3620	116 (3.2%)	778	53/778 (6.8%)	41/53 (77.4%)	26	14/26 (53.8%)	https://www.info.gov.hk/gia/gener al/202202/21/P2 022022100402.htm? fontSize=1
12	Chung Wo House, Chung On Estate (Sha Tin) ^d		1170	49 (4.2%)	560	25/560 (4.5%)	22/25 (88.0%)	11	8/11 (72.7%)	https://www.info.gov.hk/gia/gener al/202202/21/P2 022022100402.htm? fontSize=1

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No.	Name of building (Administrative district)	Date of RTD	No. of persons tested	No. (%) of persons positive	No. of flats in the building	No. (%) of flats with positive cases ^a	No. (%) of flats involved in VT ^c	No. of units with positive cases ^b	No. (%) of units involved in VT ^c	Website from HKSAR
13	Cheong Him House, Nam Cheong Estate (Sham Shui Po) ^d	21 Feb 2022	460	63 (13.7%)	224	35/224 (15.6%)	32/35 (91.4%)	13	10/13 (76.9%)	al/202202/22/P2 022022200371.htm? fontSize=1 https://www.info.gov.hk/gia/general/202202/22/P202202200651.htm?fontSize=1
14	Cheong Yat House, Nam Cheong Estate (Sham Shui Po) ^d	21 Feb 2022	640	72 (11.3%)	308	37/308 (12.0%)	31/37 (83.8%)	17	11/17 (64.7%)	al/202202/22/P2 022022200655.htm? fontSize=1 https://www.info.gov.hk/gia/general/202202/22/P202202200655.htm?fontSize=1
15	Chung Kwan House, Chung On Estate (Ma On Shan) ^d	22 Feb 2022	2000	95 (4.8%)	560	63/560 (11.3%)	58/63 (92.1%)	20	15/20 (75.0%)	al/202202/23/P2 022022300424.htm? fontSize=1 https://www.info.gov.hk/gia/general/202202/23/P202202300424.htm?fontSize=1
16	Heng Fung House, Heng On Estate (Sha Tin) ^d	22 Feb 2022	2100	160 (7.6%)	816	96/816 (11.8%)	94/96 (97.9%)	23	21/23 (91.3%)	al/202202/23/P2 022022300451.htm? fontSize=1 https://www.info.gov.hk/gia/general/202202/23/P202202300451.htm?fontSize=1
17	Lai Pak House, Lai Tsui Court (Cheung Sha Wan) ^d	24 Feb 2022	1957	228 (11.7%)	684	105/684 (15.4%)	105/105 (100%)	18	18/18 (100%)	al/202202/25/P2 022022500455.htm? fontSize=1 https://www.info.gov.hk/gia/general/202202/25/P202202500455.htm?fontSize=1
18	Royal Diamond (Tower 5A and 5B), The Wings II (Tseung Kwan O) ^e	24 Feb 2022	500	17 (3.4%)	200	6/200 (3.0%)	4/6 (66.7%)	4	2/4 (50.0%)	al/202202/25/P2 022022500262.htm? fontSize=1 https://www.info.gov.hk/gia/general/202202/25/P202202500262.htm?fontSize=1
19	Ming Tai House, On Tai Estate (Kwun Tong) ^d	24 Feb 2022	2080	216 (10.4%)	764	114/764 (14.9%)	111/114 (97.4%)	24	21/24 (87.5%)	al/202202/25/P2 022022500435.htm? fontSize=1 https://www.info.gov.hk/gia/general/202202/25/P202202500435.htm?fontSize=1
20	Block 5, On Ning Garden (Tseung Kwan O) ^e	25 Feb 2022	910	85 (9.3%)	390	47/390 (12.1%)	45/47 (95.7%)	10	8/10 (80.0%)	al/202202/26/P2 022022600433.htm? fontSize=1 https://www.info.gov.hk/gia/general/202202/26/P202202600433.htm?fontSize=1
21	Sau Wah House, Sau Mau Ping Estate (Kwun Tong) ^d	25 Feb 2022	2070	259 (12.5%)	799	148/799 (18.5%)	148/148 (100%)	20	20/20 (100%)	al/202202/26/P2 022022600352.htm? fontSize=1 https://www.info.gov.hk/gia/general/202202/26/P202202600352.htm?fontSize=1
22	Sau Yee House, Sau Mau Ping Estate (Kwun Tong) ^d	25 Feb 2022	2030	273 (13.4%)	799	179/799 (22.4%)	179/179 (100%)	20	20/20 (100%)	al/202202/26/P2 022022600465.htm? fontSize=1 https://www.info.gov.hk/gia/general/202202/26/P202202600465.htm?fontSize=1
23	Foo Wo House, Wo Che Estate (Sha Tin) ^d	26 Feb 2022	1580	309 (19.6%)	470	162/470 (34.5%)	161/162 (99.4%)	34	33/34 (97.1%)	al/202202/27/P2 022022700358.htm? fontSize=1 https://www.info.gov.hk/gia/general/202202/27/P202202700358.htm?fontSize=1
24	Shek Sau House, Shek Lei (I) Estate (Kwai Chung) ^d	27 Feb 2022	1320	247 (18.7%)	738	166/738 (22.5%)	162/166 (97.6%)	41	37/41 (90.2%)	al/202202/28/P2 022022800412.htm? fontSize=1 https://www.info.gov.hk/gia/general/202202/28/P202202800412.htm?fontSize=1
25	Heng Chui House, Tin Heng Estate (Yuen Long) ^d	27 Feb 2022	1200	124 (10.3%)	410	65/410 (15.9%)	65/65 (100%)	10	10/10 (100%)	al/202202/28/P2 022022800392.htm? fontSize=1 https://www.info.gov.hk/gia/general/202202/28/P202202800392.htm?fontSize=1
26	Heng Chun House, Tin Heng Estate (Yuen Long) ^d	27 Feb 2022	1100	118 (10.7%)	328	64/328 (19.5%)	64/64 (100%)	8	8/8/(100%)	al/202202/28/P2 022022800396.htm? fontSize=1 https://www.info.gov.hk/gia/general/202202/28/P202202800396.htm?fontSize=1

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27	Sau Fu House, Sau Mau Ping Estate (Kwun Tong) ^d	27 Feb 2022	1050	182 (17.3%)	405	96/405 (23.7%)	96/96 (100%)	15	15/15 (100%)	https://www.info.gov.hk/gia/general/202202/28/P2022022800374.htm?fontSize=1
28	Chun Ho House, Ching Chun Court (Tsing Yi) ^d	28 Feb 2022	530	45 (8.5%)	232	28/232 (12.1%)	27/28 (96.4%)	9	8/9 (88.9%)	https://www.info.gov.hk/gia/general/202203/01/P2022030100245.htm?fontSize=1
29	Sau Yin House, Sau Mau Ping Estate (Kwun Tong) ^d	28 Feb 2022	1870	382 (20.4%)	640	184/640 (28.8%)	184/184 (100%)	16	16/16 (100%)	https://www.info.gov.hk/gia/general/202203/01/P2022030100249.htm?fontSize=1
30	Fuk Yat House, Yat Tung (I) Estate (Tung Chung) ^d	28 Feb 2022	920	125 (13.6%)	320	66/320 (20.6%)	66/66 (100%)	8	8/8 (100%)	https://www.info.gov.hk/gia/general/202203/01/P2022030100377.htm?fontSize=1
31	Chun Hin House, Ching Chun Court (Tsing Yi) ^e	1 Mar 2022	520	64 (12.3%)	233	34/233 (14.6%)	33/34 (97.1%)	10	9/10 (90.0%)	https://www.info.gov.hk/gia/general/202203/02/P2022030200310.htm?fontSize=1
32	Pok Man House, Pok Hong Estate (Sha Tin) ^d	1 Mar 2022	1740	211 (12.1%)	776	130/776 (16.8%)	127/130 (97.7%)	29	26/29 (89.7%)	https://www.info.gov.hk/gia/general/202203/02/P2022030200385.htm?fontSize=1
33	Shing Tai House, On Tai Estate (Kwun Tong) ^d	1 Mar 2022	1820	180 (9.9%)	696	98/696 (14.1%)	96/98 (98.0%)	24	22/24 (91.7%)	https://www.info.gov.hk/gia/general/202203/02/P2022030200395.htm?fontSize=1
34	Kit Yat House, Yat Tung (II) Estate (Tung Chung) ^d	1 Mar 2022	1080	145 (13.4%)	400	83/400 (20.8%)	83/83 (100%)	10	10/10 (100%)	https://www.info.gov.hk/gia/general/202203/02/P2022030200293.htm?fontSize=1
35	Yiu Shing House, Tin Yiu (I) Estate (Yuen Long) ^d	3 Mar 2022	1440	223 (15.5%)	630	150/630 (23.8%)	150/150 (100%)	18	18/18 (100%)	https://www.info.gov.hk/gia/general/202203/03/P2022030300321.htm?fontSize=1
36	Tak Loong House, Tak Long Estate (Kowloon City) ^d	3 Mar 2022	1730	233 (13.5%)	960	143/960 (14.9%)	142/143 (99.3%)	22	21/22 (95.5%)	https://www.info.gov.hk/gia/general/202203/03/P2022030300336.htm?fontSize=1
37	Yiu Tai House, Tin Yiu (II) Estate (Yuen Long) ^d	3 Mar 2022	1320	232 (17.6%)	630	155/630 (24.6%)	155/155 (100%)	18	18/18 (100%)	https://www.info.gov.hk/gia/general/202203/04/P2022030400300.htm?fontSize=1
38	Tak Yu House, Tak Long Estate (Kowloon City) ^d	5 Mar 2022	1630	238 (14.6%)	960	160/960 (16.7%)	158/160 (98.8%)	27	25/27 (92.6%)	https://www.info.gov.hk/gia/general/202203/06/P2022030600231.htm?fontSize=1
39	Tak Pui House, Tak Long Estate (Kowloon City) ^d	5 Mar 2022	1620	223 (13.8%)	864	144/864 (16.7%)	143/144 (99.3%)	26	25/26 (96.2%)	https://www.info.gov.hk/gia/general/202203/06/P2022030600234.htm?fontSize=1
40	Tak Yiu House, Tak Long Estate (Kowloon City) ^d	5 Mar 2022	1450	217 (15.0%)	960	152/960 (15.8%)	151/152 (93.3%)	21	20/21 (95.2%)	https://www.info.gov.hk/gia/general/202203/06/P2022030600290.htm?fontSize=1
41	Block 5, Sherwood Court, Kingswood Villas (Yuen Long) ^e	8 Mar 2022	700	40 (5.7%)	312	27/312 (8.7%)	26/27 (96.3%)	8	7/8 (87.5%)	https://www.info.gov.hk/gia/general/202203/09/P20220309002203.htm?fontSize=1

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42	Tin Yiu House, Shun Tin Estate (Kwun Tong) ^d	8 Mar 2022	1020	315 (30.9%)	567	197/567 (34.7%)	197/197 (100%)	27	27/27 (100%)	0900343.htm?fontSize=1 https://www.info.gov.hk/gia/general/202203/09/P2022030900449.htm?fontSize=1
43	Tin Wing House, Shun Tin Estate (Kwun Tong) ^d	8 Mar 2022	740	163 (22.0%)	350	106/350 (30.3%)	106/106 (100%)	14	14/14 (100%)	https://www.info.gov.hk/gia/general/202203/09/P2022030900332.htm?fontSize=1
44	Oi Chi House, Yau Oi Estate (Tuen Mun) ^d	11 Mar 2022	1720	295 (17.2%)	820	200/820 (24.4%)	200/200 (100%)	30	30/30 (100%)	https://www.info.gov.hk/gia/general/202203/12/P2022031200183.htm?fontSize=1
45	Fook Yuet House, Fortune Estate (Sham Shui Po) ^d	11 Mar 2022	1304	215 (16.5%)	731	154/731 (21.1%)	151/154 (98.1%)	31	28/31 (90.3%)	https://www.info.gov.hk/gia/general/202203/12/P2022031200169.htm?fontSize=1
46	Hang Lai House, Cheung Hang Estate (Tsing Yi) ^d	11 Mar 2022	1760	43 (2.4%)	840	39/840 (4.6%)	32/39 (82.1%)	17	10/17 (58.8%)	https://www.info.gov.hk/gia/general/202203/12/P2022031200228.htm?fontSize=1
47	Chun Tat House, On Tat Estate (Kwun Tong) ^d	11 Mar 2022	1440	134 (9.3%)	868	97/868 (11.2%)	95/97 (97.9%)	22	20/22 (90.9%)	https://www.info.gov.hk/gia/general/202203/12/P2022031200253.htm?fontSize=1
48	Tun Man House, Oi Man Estate (Ho Man Tin) ^d	11 Mar 2022	1400	223 (15.9%)	520	148/520 (28.5%)	146/148 (98.6%)	18	15/18 (83.3%)	https://www.info.gov.hk/gia/general/202203/12/P2022031200248.htm?fontSize=1
49	On Tung House, Tung Tau (II) Estate (Wong Tai Sin) ^d	11 Mar 2022	455	82 (18.0%)	240	51/240 (21.3%)	48/51 (94.1%)	18	15/18 (83.3%)	https://www.info.gov.hk/gia/general/202203/12/P2022031200217.htm?fontSize=1
50	Gladiolus House, So Uk Estate (Sham Shui Po) ^d	14 Mar 2022	597	50 (8.4%)	299	47/299 (15.7%)	44/47 (93.6%)	15	12/15 (80.0%)	https://www.info.gov.hk/gia/general/202203/15/P2022031500202.htm?fontSize=1
51	Tip Mo House, Butterfly Estate (Tuen Mun) ^d	14 Mar 2022	1260	281 (22.3%)	936	205/936 (21.9%)	194/205 (94.6%)	59	48/59 (81.4%)	https://www.info.gov.hk/gia/general/202203/15/P2022031500207.htm?fontSize=1
52	Fu Leung House, Fu Cheong Estate (Sham Shui Po) ^d	14 Mar 2022	177	48 (27.1%)	150	39/150 (26.0%)	38/39 (97.4%)	10	9/10 (90.0%)	https://www.info.gov.hk/gia/general/202203/15/P2022031500212.htm?fontSize=1
53	Tin Chi House, Shun Tin Estate (Kwun Tong) ^d	14 Mar 2022	1470	241 (16.4%)	731	166/731 (22.7%)	164/166 (98.8%)	32	30/32 (93.8%)	https://www.info.gov.hk/gia/general/202203/15/P2022031500258.htm?fontSize=1
54	Lee Fu House, Shun Lee Estate (Kwun Tong) ^d	14 Mar 2022	1120	168 (15.0%)	620	121/620 (19.5%)	112/121 (92.6%)	45	36/45 (80.0%)	https://www.info.gov.hk/gia/general/202203/15/P2022031500256.htm?fontSize=1
55	Tin Kam House, Shun Tin Estate (Kwun Tong) ^d	14 Mar 2022	1500	220 (14.7%)	737	224/737 (30.4%)	223/224 (99.6%)	36	35/36 (97.2%)	https://www.info.gov.hk/gia/general/202203/15/P2022031500260.htm?fontSize=1
56			1560		714			34		

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	Wing Yuen House, Chuk Yuen (South) Estate (Wong Tai Sin) ^d	14 Mar 2022		253 (16.2%)		179/714 (25.1%)	178/179 (99.4%)		33/34 (97.1%)	https://www.info.gov.hk/gia/general/202203/15/P2022031500216.htm?fontSize=1
57	Tin Chu House, Shun Tin Estate (Kwun Tong) ^d	15 Mar 2022	1280	276 (21.6%)	731	170/731 (23.3%)	169/170 (99.4%)	34	33/34 (97.1%)	https://www.info.gov.hk/gia/general/202203/16/P2022031600260.htm?fontSize=1
58	Fu Yuen House, Chuk Yuen (South) Estate (Wong Tai Sin) ^d	15 Mar 2022	1500	227 (15.1%)	714	154/714 (21.6%)	152/154 (98.7%)	32	30/32 (93.8%)	https://www.info.gov.hk/gia/general/202203/16/P2022031600285.htm?fontSize=1
59	Sin Sam House, Lung Hang Estate (Sha Tin) ^d	15 Mar 2022	1630	294 (18.0%)	710	196/710 (21.6%)	195/196 (99.5%)	34	33/34 (97.1%)	https://www.info.gov.hk/gia/general/202203/16/P2022031600322.htm?fontSize=1
60	Tip Ling House, Butterfly Estate (Tuen Mun) ^d	15 Mar 2022	1130	209 (18.5%)	864	149/864 (17.2%)	130/149 (87.2%)	56	37/56 (66.1%)	https://www.info.gov.hk/gia/general/202203/16/P2022031600308.htm?fontSize=1
61	Hang Chun House, Cheung Hang Estate (Tsing Yi) ^d	15 Mar 2022	1530	105 (6.9%)	746	84/746 (11.3%)	80/84 (95.2%)	21	17/21 (81.0%)	https://www.info.gov.hk/gia/general/202203/16/P2022031600337.htm?fontSize=1
62	Lai Kuk House, Lai Kok Estate (Sham Shui Po) ^d	15 Mar 2022	738	86 (11.7%)	480	65/480 (13.5%)	53/65 (81.5%)	35	19/35 (54.3%)	https://www.info.gov.hk/gia/general/202203/16/P2022031600250.htm?fontSize=1
63	Sheung Sam House, Lung Hang Estate (Sha Tin) ^d	17 Mar 2022	1320	120 (9.1%)	710	96/710 (13.5%)	87/96 (90.6%)	31	22/31 (71.0%)	https://www.info.gov.hk/gia/general/202203/18/P2022031800281.htm?fontSize=1
64	Lei Yee House, Ap Lei Chau Estate (Aberdeen) ^d	17 Mar 2022	940	61 (6.5%)	530	49/530 (9.2%)	35/49 (71.4%)	26	12/26 (46.2%)	https://www.info.gov.hk/gia/general/202203/18/P2022031800301.htm?fontSize=1
65	Tip Chui House, Butterfly Estate (Tuen Mun) ^d	17 Mar 2022	1180	134 (11.4%)	936	106/936 (11.3%)	86/106 (81.1%)	52	32/52 (61.5%)	https://www.info.gov.hk/gia/general/202203/18/P2022031800328.htm?fontSize=1
66	Wu Fai House, Wu King Estate (Tuen Mun) ^d	17 Mar 2022	1350	136 (10.1%)	731	107/731 (14.6%)	100/107 (93.5%)	32	25/32 (78.1%)	https://www.info.gov.hk/gia/general/202203/18/P2022031800349.htm?fontSize=1
67	Block 5, Po Tin Estate (Tuen Mun) ^{d,f}	17 Mar 2022	827	57 (6.9%)	1008	52/1008 (5.2%)	39/52 (75.0%)	28	15/28 (53.6%)	https://www.info.gov.hk/gia/general/202203/18/P2022031800382.htm?fontSize=1
68	Block 4, Po Tin Estate (Tuen Mun) ^{d,f}	18 Mar 2022	800	61 (7.6%)	1008	53/1008 (5.3%)	40/53 (75.5%)	28	15/28 (53.6%)	https://www.info.gov.hk/gia/general/202203/19/P2022031900222.htm?fontSize=1
69	Fu Pong House, Tai Wo Hau Estate (Kwai Chung) ^d	18 Mar 2022	710	55 (7.7%)	440	43/440 (9.8%)	41/43 (95.3%)	15	13/15 (86.7%)	https://www.info.gov.hk/gia/general/202203/19/P2022031900197.htm?fontSize=1
70	Tip Sum House, Butterfly Estate (Tuen Mun) ^d	18 Mar 2022	1080	131 (12.1%)	816	106/816 (13.0%)	88/106 (83.0%)	49	31/49 (63.3%)	https://www.info.gov.hk/gia/general/202203/19/P20220319002203.htm?fontSize=1

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71	Kin Ching House, Kin Ming Estate (Tseung Kwan O) ^d	18 Mar 2022	1700	91 (5.4%)	799	65/799 (8.1%)	62/65 (95.4%)	18	15/18 (83.3%)	1900231.htm?fontSize=1 https://www.info.gov.hk/gia/general/202203/19/P2022031900218.htm?fontSize=1
72	Fu Man House, Tai Wo Hau Estate (Kwai Chung) ^d	18 Mar 2022	790	45 (5.7%)	460	34/460 (7.4%)	33/34 (97.1%)	14	13/14 (92.9%)	https://www.info.gov.hk/gia/general/202203/19/P2022031900235.htm?fontSize=1
73	Kai Fai House, Choi Wan (II) Estate (Wong Tai Sin) ^d	18 Mar 2022	1687	165 (9.8%)	580	128/580 (22.1%)	126/128 (98.4%)	33	31/33 (93.9%)	https://www.info.gov.hk/gia/general/202203/19/P2022031900253.htm?fontSize=1

HKSAR, Government of Hong Kong Special Administrative Region, China; VT, vertical transmission.

^a A flat is a living unit (ranging from 1 bedroom to 3 bedrooms in size) located on the same floor of a residential building.

^b A unit is a flat located at different positions (may be facing the different direction) on the same floor of the residential building. There are up to 68 units per floor in the public residential building in Hong Kong.

^c Vertical transmission refers to the airborne transmission of SARS-CoV-2 via the drainage pipes to the units above or below on different floors of the residential building.

^d Public residential building.

^e Private residential building.

^f Temporal residential building with low occupancy.

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