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Risk of air and surface contamination of SARS-CoV-2 in isolation wards and its relationship with patient and environmental characteristics

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**ABSTRACT**

Air and surface contamination of the SARS-CoV-2 have been reported by multiple studies. However, the evidence is limited for the change of environmental contamination of this virus in the surrounding of patients with COVID-19 at different time points during the course of disease and under different conditions of the patients. Therefore, this study aims to understand the risk factors associated with the appearance of SARS-CoV-2 through the period when the patients were staying in the isolation wards. In this study, COVID-19 patients admitted to the isolation wards were followed up for up to 10 days for daily collection of air and surface samples in their surroundings. The positivity rate of the environmental samples at different locations was plotted, and multiple multi-level mixed-effect logistic regressions were used to examine the association between the positivity of environmental samples and their daily health conditions and environmental factors. It found 6.6 % of surface samples (133/2031 samples) and 2.1 % of air samples (22/1075 samples) were positive, and the positivity rate reached to peak when the patients were staying in the isolation wards. The virus was more likely to present at bedrail, patients’ cough at the day of sampling, lower Ct values of latest test for respiratory tract samples, and pre-existing respiratory or cardiovascular conditions. The finding can be used to guide the hospital infection control strategies by identifying high-risk areas and patients. Extra personal hygiene precautions and equipment for continuously environmental disinfection can be used for these high-risk areas and patients to reduce the risk of hospital infection.

1. Introduction

Airborne transmission of SARS-CoV-2 has been shown and confirmed by various laboratory experiments, epidemiological studies on outbreaks, and environmental surveillance in healthcare and community settings. A systematic review found that air samples positive for RNA of SARS-CoV-2 were present in the intensive care units for COVID-19 patients, including those with negative pressure ventilation system (Noorimotlagh et al., 2021). Another study performing air sampling in three airborne infection isolation rooms in general wards found particles positive for the viral RNA in two out of the three rooms, even with a ventilation rate of 12 air changes per hour (Chia et al., 2020). Another systematic review estimated that 17 % of the air samples were found positive in various settings in the hospitals (Birgand et al., 2020). In the community setting, evidence of airborne transmission was found in a church infecting 12 secondary cases sitting up to 15 m away from the...
index patient without any close physical contact (Katelaris et al., 2021). Small droplets generated from speech could have a half-life of around 8 min in a closed environment (Stadnytska et al., 2020). Apart from air contamination, surface contamination of the virus was reported by several studies as well (Gonçalves et al., 2021). All these contaminations may lead to indirect transmission of the virus from the media or environment to humans (Hu et al., 2021; Ijaz et al., 2021; Xie et al., 2020). Among different settings, hospital setting is still one of the high-risk areas due to direct exposure to COVID-19 patients.

Therefore, there is a risk of nosocomial infection for the healthcare workers and the patients without COVID-19, which may lead to an infectious disease outbreak in the hospital or the community (Abbas et al., 2021; Nielsen, 2009). In the early stage of COVID-19 pandemic (before the end of April 2020) where the control strategies were not fully in place, a study in the UK and Italy found that 12.5% of all infections were acquired in the hospital (Carter et al., 2020). This rate was reduced to less than 1% afterwards with stricter control measures, while the risk for healthcare workers to get infected is around twice as those who only stay in communities (Evans et al., 2021; Rhee et al., 2020). Regarding the route of transmission, airborne spread of virus has been associated with certain high risk aerosolizing procedures such as endotracheal intubation, BIPAP, high-flow oxygen therapy and others as well (Howard, 2020; Klompas et al., 2021; Zietsman et al., 2019). Coughing by itself also produces a lot of aerosols. While the facemask can avoid the spread of such aerosols in front, the two sides of the facemask could pose an issue (Fang et al., 2008). Additionally, the SARS-CoV-2 can survive with a viral load that can lead to human infection for up to 21 days on steel, glass and paper, and survive for 9 h on human skin at room temperature (Bezdinasaab et al., 2021; Hirose et al., 2021; Marzoli et al., 2021), so good hand hygiene should be performed in addition to use of facemasks to provide protection against infection from contaminated surfaces.

Considering that the SARS-CoV-2 is more infectious than SARS-CoV-1 and MERS-CoV, knowledge about the airborne potential of the virus is important and urgent to facilitate medical and nursing care of such patients while minimizing risks of cross-infection to other patients. However, although multiple studies have been conducted to detect SARS-CoV-2 in various areas inside hospitals, the evidence of environmental contamination at different time points along the course of the disease is limited. This prohibits the ability to assess the change in degree of contamination along course of the disease and under various environmental and patient conditions. A follow-up of these patients for environmental sampling at their surroundings and recording of their daily status would be beneficial. This study aims to detect the degree of SARS-CoV-2 environmental contamination in the surroundings of the patients and understand the risk factors associated with the level of contamination throughout the course of disease of the patients, including the patient’s clinical status, humidity and temperature of the environment and the number of confirmed patients being treated.

2. Materials and methods

A prospective longitudinal study was conducted to follow up the patients with COVID-19 for up to 10 days to detect presence of SARS-CoV-2 in the isolation room where they were staying for treatment in a Hong Kong hospital from August 2020 to March 2021. Microbiological samples of inanimate surfaces (i.e. not including surfaces of human bodies) and air were collected to detect for the presence of the virus. The study was approved by the relevant research ethics committee, and written informed consents were obtained from the patients prior to the study.

2.1. Study participants

Patients diagnosed with COVID-19 who have been admitted to negative pressure isolation room for treatment in the study hospital were invited to participate in the study. Patients who were unconscious, suffering from cognitive impairment or deemed too weak upon assessment by in-charge doctors to make a good cough as required by the study were excluded. The patients were first screened by the doctor in-charge for their eligibility to join the study, got explained and were invited by the doctor in-charge to participate in the study and sign the consent form. The number of patients invited for the study was subject to availability of the air sampling equipment.

2.2. Sample collection and processing

Air and surface samples for every recruited patient were collected every day for up to 10 consecutive days when they stayed in the isolation ward. The sample collection stopped before day 10 when patients were discharged from the hospital, moved to other wards (e.g., intensive care unit), or deceased. On each day for each patient, four air samples and eight surface samples were collected. The sampling locations and physical layout of an isolation room can be found in Fig. 1, which consist of a four-bedded cubicle and an anteroom between the cubicle and the central corridor outside the isolation room. Air samples in the cubicle were collected at the bed table and at head-end of bed near the grille covering the exhaust outlet of the ventilation system in the cubicle before and immediately after the patients were asked to cough three times with a mask on. One air sample was collected at each anteroom and another one was collected at corridor of the isolation ward outside the negative pressure isolation room daily. The surface samples were collected before the patients were asked to cough in the cubicle (bedrail, bedside table, medical equipment and personal item such as mobile phone) and the anteroom (doorknob, trolley handle, hand sanitizer dispenser, waste bin step). Besides these daily-collected samples, one air sample was collected every week at the centre of the isolation room when one of the patients inside this room was asked to cough, to examine whether the virus could spread to places with wider range. As a blank reference, one air sample was collected at an empty isolation room every week.

Air samples were collected using Sartorius AirPort MD8 Air Sampler (Sartorius AG, Germany) with sterile gelatine filters (80 mm in diameter, Sartorius AG). The air flow rate was approximately 50 l per minute, and collection of each air sample lasted for 20 min so that 1000 litre of air would pass through the gelatine filter. Upon dismounting the holding frame, the gelatine filters were then removed in the laboratory and dissolved in 15 mL phosphate buffered saline (PBS) for further processing. The surface samples were collected using the swab prefertilized by viral transport medium (VTM). For surfaces with larger areas (e.g., tabletop), samples were collected by wiping in an “S” pattern to cover a 10 cm × 10 cm area. For small items (e.g., mobile phone), the samples were collected by wiping all available surface of the item in one direction. The swabs were then suspended in 5 mL VTM for further transportation and processing.

The environmental samples collected in both parts of the study were tested for the presence of SARS-CoV-2 nucleic acid with real-time reverse transcription polymerase chain reaction (RT-PCR) on Cobas 6800 system (Roche Diagnostics Ltd.). All the specimens were processed and tested at the spare facilities in one of the local World Health Organization (WHO) COVID-19 reference laboratories in Hong Kong. The testing method and corresponding parameters for the laboratory tests were validated using clinical isolated inactivated cultured intact virus (Qnostics Ltd.) prior to commencement of the study. The environmental samples were stored at 4 °C before processing. The samples were processed and tested within 48 h after collection. If the tests were unable to be carried out within 48 h, the samples would be stored at −70 °C, and tested within one month accordingly. The outcome of the RT-PCR test included qualitative binary results of positive or negative towards the viral RNA and cycle threshold (Ct) values.
2.3. Collection of other information

Apart from sample collection, demographical and health-related information as well as other environmental information that could affect the sample outcomes were collected. The date of birth, sex, pre-existing conditions, symptom onset day (or the day of first positive test if the patient was asymptomatic) and hospital admission date were collected at baseline. At baseline and upon each day of follow-up, the COVID-19 compatible symptoms, mask-wearing during the air sampling, use of ventilator to support respiration, time of last disinfection performed as well as room temperature and humidity were recorded. The Ct values of all the PCR tests performed by the hospital for the patients during their stay in the isolation wards for surveillance and treatment for COVID-19 were retrieved from their health records.

2.4. Statistical analysis

Frequencies of positive surface and air samples were described for each sampling locations. Comparison was made using Chi-square tests according to presence of symptoms (including before and after coughing), duration from symptom onset or first positive test, disinfection status as well as among patients with different age, sex and chronic conditions in cross-tabulations for the air and surface samples collected daily in the isolation room (i.e. the samples collected in the anteroom were not included for this part of analysis as they cannot be linked to the characteristics of a particular patient). Following this, multiple multi-level mixed-effect logistic regression with clustered samples at separate locations each day and at different days of an individual was used to examine the association between the positivity rate of these daily-collected samples in the isolation room and aforementioned factors. The dependent variable was the qualitative binary test result of the air or surface samples (positive/negative). The independent variables included age, sex, pre-existing respiratory/ cardiovascular conditions, cough, fever, latest PCR test result, whether wearing facemask during sampling, time since last disinfection, number of patients in the same room, and environmental temperature and humidity. Test for multicollinearity showed that duration from onset of symptom or first positive test was highly correlated with other independent variables (e.g., daily symptoms and viral test results of the patients), and therefore it was removed from the model. In the first model, binary outcomes (positive/negative) of latest PCR test were used as independent variable in the regression. In the second model, the Ct value of the latest PCR test, indicating the viral load, was used in replacement of its binary outcome. In the third model, one-day lag effect of the daily symptoms of the patients (cough and fever on last day) on the positivity rate were examined in the analysis, with control of the symptoms on that day and other covariates. Sensitivity analysis was conducted for the first and second model separately for different time since latest disinfection, as it is an important factor that influence the positivity rate. Restricted cubic spline with five knots based on Harrell’s recommendation (at 5th,
27.5th, 50th, 72.5th and 95th percentile) was used to test the potential non-linear relationship between the positivity rate and environment temperature and humidity, as well as the Ct value of the PCR test in the second model.

3. Results

3.1. Characteristics of participants and samples

A total of 51 patients with COVID-19 were recruited. Environmental samples and information of the disease progress were collected for 348 patient-days in total. For these 51 patients, median follow-up day was 8 (IQR = 6) days. Of them, 32 (62.8 %) were female, average age was 50.1 years (SD: 21.5 years). Thirty-two of them (62.8 %) suffered from chronic conditions, including 12 of them (23.5 %) who had cardiovascular and/or respiratory conditions (Table 1). A total of 3291 samples (2031 surface samples and 1260 air samples) were collected and processed during daily follow-up of the patients, including 3106 daily samples (2031 surface and 1075 air samples) inside the isolation room (2212 samples, including 1318 surface and 894 air samples) and anteroom (894 samples, including 713 surface and 181 air samples), 158 daily air sample in the corridor of the isolation ward outside isolation room, and 13 weekly air samples inside an empty isolation room.

3.2. Positivity rate of the samples by separate locations

All the 158 air samples collected in the corridor outside the isolation room, all the 14 weekly air samples collected at the centre of an isolation room, and the 13 weekly samples collected in an empty isolation room were tested to be negative. Among the daily samples collected inside the isolation room (n = 2212, not including the 14 weekly air samples at the centre of the room) / anteroom (n = 94), it can be found that 6.6 % surface samples and 2.1 % air samples were tested positive. The positivity rate of surface samples was significantly higher than air samples (P < 0.05). The surface samples collected in the isolation room were more likely to be positive than anteroom (6.7 % versus [vs] 1.0 %, P < 0.05) (Table 2). In the isolation room, the positivity rate was found higher on personal items (10.9 %, mostly mobile phone), bedrail (11.3 %), and medical equipment (10.7 %) than bed table (6.1 %). In the anteroom, the positivity rate was slightly higher on waste bin step (2.8 %), hand sanitizer dispenser (0.6 %) and handle of trolley (0.6 %) than doorknob (0 %) (Fig. 1). As for air samples, there were 2.6 % samples collected at bed table and 1.9 % samples at bedside after patient coughing, and 2.6 % samples collected before patient coughing showing positive results, while no air sample at anteroom was found positive (Fig. 1).

3.3. Positivity rate according to patient’s characteristics

Table 3 shows the positivity rate of the 2212 samples (1318 surface samples and 894 air samples) collected daily inside the isolation room according to different characteristics of the patients. The overall positivity rate was significantly higher among those with COVID-19 compatible symptoms at the day of sampling than those without these symptoms (7.9 % vs 5.2 %, P < 0.05), including those having fever (10.5 % vs 5.9 %, P < 0.05) and cough (8.8 % vs 5.4 %, P < 0.05). Moreover, shortness of breath and coughing within 3 days did not change the positivity rate. More samples were found positive among those with respiratory tract samples tested positive for SARS-CoV-2 (deep throat saliva or nasal swabs, 6.9 % vs 2.2 %, P < 0.05). The positivity rate was 7.3 % at 0–1 day after symptom onset or first positive test result and became higher in 2–3 days (12.7 %), and decreased as time passed (4–7 days: 10.0 %, 8–10 days: 8.3 %, 11–13 days: 4.0 %, 14+ days: 0.9 %). Moreover, the duration since last disinfection of the room could also change the positivity rate. The positivity rate was 6.4 % and 5.3 % at < 1 h and between 1 and 3 h after adequate disinfection, while it became greater in 3–6 h (8.8 %) and 6–12 h (14.5 %). For number of patients within the same room, the positivity rate was marginally higher among those rooms with greater number of patients (5 vs 4 vs 3 vs 1–2 patients: 16.7 %, 7.4 %, 6.7 %, and 4.2 %, P = 0.080).

Table 3 also shows the results separately for surface samples and air samples. Positivity rate of air samples was found significantly associated with time of the latest disinfection (P < 0.05). It became higher six hours after the latest disinfection (after six hours vs within six hours: 15.3 % vs 1.1 %–2.6 %). As for surface samples, the pattern of their positivity rate was similar to the pattern in overall results, including significant higher positivity rate (P < 0.05) among those who had symptoms (11.0 % vs 7.6 %), cough (12.2 % vs 7.8 %), fever (16.0 % vs 8.1 %), 2–7 days since symptom onset/first positive test/admission to the ward (over 10 %), and higher number of COVID-19 patients in the same room (5 vs 4 vs 3 vs 1–2 patients: 25.0 %, 12.2 %, 8.6 %, and 5.7 %). As time since the latest disinfection was found to be an important factor that influence the positivity rate of the sample, a supplementary analysis was conducted to examine the difference in positivity rate according to patient characteristics with control of time since disinfection and type of the sample (air/surface). The results are shown in Supplementary Table S1. Within 3 h after disinfection, presence of symptoms (10.2 % vs 6.1 %), fever (18.2 % vs 6.5 %), cough (11.5 % vs 6.5 %), 2–10 days since symptom onset/first positive test/admission to the ward, and greater number of patients in the same room (4 vs 3 vs 1–2 patients: 10.9 %, 6.8 %, and 2.8 %) contributed to significantly greater

| Type of samples | Negative [N (%)] | Positive [N (%)] | Total [N (%)] | P value |
|-----------------|-----------------|-----------------|---------------|---------|
| Surface         | 1898 (93.5)     | 133 (6.6)       | 2031 (100.0)  | <0.001  |
| Air             | 1053 (98.0)     | 22 (2.1)        | 1075 (100.0)  |         |
| Locations       |                 |                 |               |         |
| Isolation room  | 2065 (93.4)     | 147 (6.7)       | 2212 (100.0)  | <0.001  |
| Anteroom        | 885 (99.0)      | 9 (1.0)         | 894 (100.0)   |         |
| Total           | 2951 (95.0)     | 155 (5.0)       | 3106 (100.0)  |         |

Note: 1. Air samples collected weekly at the centre of the isolation room (n = 14) are not included in calculation of these positivity rates.

| Age group       | N   | Percentage (%) |
|-----------------|-----|----------------|
| 0–20 years      | 1   | 2.0            |
| 21–40 years     | 16  | 31.4           |
| 41–60 years     | 17  | 33.3           |
| 61 + years      | 17  | 33.3           |
| Sex             |     |                |
| Male            | 19  | 37.3           |
| Female          | 32  | 62.8           |
| Chronic disease | 32  | 62.8           |
| Cardiovascular/respiratory disease | 12 | 23.5 |
| Hypertension    | 10  | 19.6           |
| Coronary artery disease | 1 | 2.0 |
| COPD            | 3   | 5.9            |
| Cerebrovascular incident | 1 | 2.0 |
| Asthma          | 2   | 3.9            |
| Diabetes        | 4   | 7.8            |

| Mean/ Median    | SD/ IQR |
|-----------------|---------|
| Days since symptom onset/first positive test at baseline | 7.8 / 7.0 | 6.8 / 8.0 |
| Days since admission to the ward at baseline          | 4.4 / 3.0 | 4.6 / 5.0 |
| Days of follow-up                                    | 6.8 / 8.0 | 2.8 / 6.0 |
| Total                                                   | 51       | 100.0       |
Table 3

Positivity rate of surface and air samples according to various factors.

| Overall | Surface samples only | Air samples only |
|---------|----------------------|------------------|
| Presence of COVID-19 compatible symptoms |
| No 1147 (92.1) 98 (7.9) 1245 (100.0) | 0.013* | 570 (92.4) 47 (7.6) 617 (100.0) | 0.034* | 390 (98.5) 6 (1.5) 396 (100.0) |
| Yes 960 (89.5) 53 (5.2) 1013 (100.0) | | 664 (89.0) 82 (11.0) 746 (100.0) | | 483 (96.8) 16 (3.2) 499 (100.0) |
| Fever on the day of sampling |
| No 1757 (94.1) 110 (5.9) 1867 (100.0) | 0.001* | 1039 (91.9) 92 (8.1) 1131 (100.0) | <0.001* | 718 (97.6) 18 (2.5) 736 (100.0) |
| Yes 350 (89.5) 41 (10.5) 391 (100.0) | | 195 (84.1) 37 (16.0) 232 (100.0) | | 155 (97.5) 4 (2.5) 159 (100.0) |
| Cough on the day of sampling |
| No 1315 (94.6) 75 (5.4) 1390 (100.0) | 0.002* | 779 (92.2) 66 (7.8) 845 (100.0) | 0.008* | 536 (98.4) 9 (1.7) 545 (100.0) |
| Yes 792 (91.2) 76 (8.8) 868 (100.0) | | 455 (87.8) 63 (12.2) 518 (100.0) | | 337 (96.3) 13 (3.7) 350 (100.0) |
| Cough in past 3 days |
| No 1008 (94.3) 61 (5.7) 1069 (100.0) | 0.077 | 595 (91.7) 54 (8.3) 649 (100.0) | 0.169 | 413 (98.3) 7 (1.7) 420 (100.0) |
| Yes 1099 (92.4) 90 (7.6) 1189 (100.0) | | 639 (89.5) 75 (10.5) 714 (100.0) | | 460 (96.8) 15 (3.2) 475 (100.0) |
| Shortness of breath on the day of sampling |
| No 1986 (93.2) 145 (6.8) 2131 (100.0) | 0.362 | 1163 (90.4) 123 (9.6) 1286 (100.0) | 0.606 | 823 (97.4) 22 (2.6) 845 (100.0) |
| Yes 121 (95.3) 6 (4.7) 127 (100.0) | | 71 (92.2) 6 (7.8) 77 (100.0) | | 50 (100.0) 0 (0.0) 50 (100.0) |
| Latest SARS-CoV-2 test |
| Negative 132 (97.8) 3 (2.2) 135 (100.0) | 0.034* | 80 (96.4) 3 (3.6) 83 (100.0) | 0.064 | 52 (100.0) 0 (0.0) 52 (100.0) |
| Positive 1939 (93.1) 144 (6.9) 2083 (100.0) | | 1134 (90.3) 122 (9.7) 1256 (100.0) | | 805 (97.3) 22 (2.7) 827 (100.0) |
| Duration since symptom onset/first positive test (whichever is earlier) |
| 0–1 day 38 (92.7) 3 (7.3) 41 (100.0) | <0.001* | 22 (91.7) 2 (8.3) 24 (100.0) | <0.001* | 16 (94.1) 1 (5.9) 17 (100.0) |
| 2–3 days 138 (87.3) 20 (12.7) 158 (100.0) | | 80 (83.3) 16 (16.7) 96 (100.0) | | 58 (93.6) 4 (6.5) 62 (100.0) |
| 4–7 days 502 (90.0) 56 (10.0) 558 (100.0) | | 286 (85.1) 50 (14.9) 336 (100.0) | | 216 (97.3) 6 (2.7) 222 (100.0) |
| 8–10 days 485 (91.7) 44 (8.3) 529 (100.0) | | 283 (88.4) 37 (11.6) 320 (100.0) | | 202 (96.7) 7 (3.3) 209 (100.0) |
| 11–13 days 505 (96.0) 21 (4.0) 526 (100.0) | | 299 (94.6) 17 (5.4) 316 (100.0) | | 206 (98.1) 4 (1.9) 210 (100.0) |
| 14+ days 328 (99.1) 3 (0.9) 331 (100.0) | | 196 (98.5) 3 (1.5) 199 (100.0) | | 132 (100.0) 0 (0.0) 132 (100.0) |
| Wearing mask during sampling | Not always 1685 (93.4) 120 (6.7) 1805 (100.0) | 0.819 | 974 (90.4) 103 (9.6) 1077 (100.0) | 0.861 | 711 (97.7) 17 (2.3) 728 (100.0) |
| Always 415 (93.1) 31 (7.0) 446 (100.0) | | 256 (90.8) 26 (9.2) 282 (100.0) | | 159 (97.0) 5 (3.1) 164 (100.0) |
| Number of COVID-19 patients in the same isolation room |
| 1–2 patients 384 (95.8) 17 (4.2) 401 (100.0) | 0.080 | 230 (94.3) 14 (5.7) 244 (100.0) | 0.031* | 154 (98.1) 3 (1.9) 157 (100.0) |
| 3 patients 712 (93.3) 51 (6.7) 763 (100.0) | | 424 (91.4) 40 (8.6) 464 (100.0) | | 288 (96.3) 11 (3.7) 299 (100.0) |
| 4 patients 995 (92.6) 80 (7.4) 1075 (100.0) | | 571 (88.8) 72 (11.2) 643 (100.0) | | 424 (98.2) 8 (1.9) 432 (100.0) |
| 5 patients 10 (83.3) 2 (16.7) 12 (100.0) | | 6 (75.0) 2 (25.0) 8 (100.0) | | 4 (100.0) 0 (0.0) 4 (100.0) |
| 11–20 1576 (93.8) 104 (6.2) 1680 (100.0) | | 911 (90.9) 91 (9.1) 1002 (100.0) | | 665 (98.1) 13 (1.9) 678 (100.0) |
| 21–30 351 (92.4) 29 (7.6) 380 (100.0) | | 208 (89.7) 24 (10.3) 232 (100.0) | | 143 (96.6) 5 (3.4) 148 (100.0) |
| Total 2107 (93.3) 151 (6.7) 2258 (100.0) | | 1234 (90.5) 129 (9.5) 1363 (100.0) | | 873 (97.5) 22 (2.5) 895 (100.0) |

* P < 0.05.
positivity rate in surface samples (P < 0.05). Two to seven days since symptom onset/first positive test/admission to the ward and greater number of patients in the same room were also associated with greater positivity rate of air sample within 3 h after disinfection. For samples collected over 3 h after disinfection, higher positivity rate in surface samples was more likely to present at the beginning of disease onset or isolation ward admission, while there were no significant difference in positivity rate according to other characteristics.

3.4. Model estimations for influence of patient and environmental characteristics

Table 4 shows the outcomes of the first model (n = 2212). It was found that coughing contributed to a greater likelihood of having positive samples in the isolation room (adjusted odds ratio [AOR]: 2.18, 95 % confidence interval [CI]: 1.37–3.48) The likelihood of positive samples was also found to be marginally higher for patients with positive results in latest SARS-CoV-2 testing (AOR: 2.99, 95 %CI: 0.83–10.75). Regarding individual-level factors, positive samples were more likely to be found in the surroundings of patients with cardiovascular and/or respiratory conditions (AOR: 2.07, 95 %CI: 1.02–4.22). For air samples alone, cough could lead to greater likelihood of positive air samples (AOR: 3.30, 95 %CI: 1.09–10.03). For surface sample alone, positive surface sample was found associated with patients with cardiovascular and/or respiratory conditions (AOR: 2.57, 95 %CI: 1.12–5.85), fever (AOR: 1.90, 95 %CI: 1.08–3.35) and cough (AOR: 2.05, 95 %CI: 1.22–3.44).

From the second model (Supplementary table S2), it found that the likelihood to find a positive environmental sample decreased as the Ct value increased (Fig. 2). Using a Ct value of 35 as reference, the likelihood of positive sample was significantly higher when the Ct value was increased (Fig. 3). A decreasing trend of positivity likelihood was found as the temperature increased from 18 °C to 24 °C, while no significant difference was found for samples collected at different humidity. From the third model (Supplementary table S3), lag effect of the symptoms on the positivity rate was examined; however, it was found that cough and fever in the previous day did not affect the likelihood of positive samples. In the sensitivity analysis for first and second model (Supplementary table S4), cough was found consistently associated with positive samples within 3 h after disinfection. For samples collected over 3 h after disinfection, cough and cardiovascular/respiratory condition were not significantly associated with positive samples when controlling for Ct values of patient’s latest viral test.

4. Discussion

This study followed up the patients with COVID-19 for up to 10 days for determination of the degree of SARS-CoV-2 contamination in the isolation rooms that they were staying in. This is one of the limited number of studies that longitudinally follow-up the patients during entire or majority period of the course of disease to look for evidence of environmental contamination of this virus, so that the virus’s ability to contaminate the environment where the patients stay can be examined at different time points and under various environmental and patient conditions. The findings can be used to devise effective strategies to mitigate the risks and reduce the chances of nosocomial infections.

From the study, 5 % of all the environmental samples collected in the isolation room, anteroom, and the corridor outside the anteroom were found positive for SARS-CoV-2. The positivity rate, indicating the degree of environmental contamination and implying the risk of airborne and surface transmission of the virus, was relatively lower than the rate summarized by a previous systematic review of 24 cross-sectional studies collecting air samples in patient’s environment, which found a 17.4 % positivity rate in all air samples, including 13.1 % in negative pressure room (Birgand et al., 2020). A more recent systematic review revealed that positivity rate of surfaces in the COVID-19 isolation wards and overall healthcare setting was around 24.2 % and 17.3 %, respectively (Goncalves et al., 2021). The difference in the positivity rate

Table 4

| Positive sample (overall) | Positive sample (surface sample only) | Positive sample (air sample only) |
|--------------------------|--------------------------------------|----------------------------------|
| AOR 95 %CI | AOR 95 %CI | AOR 95 %CI |
|---|---|---|---|---|---|
| Age group (“0–20 yrs” as reference) | | | | | |
| 21–40 yrs | 3.94 | (0.87, 17.93) | 5.38 | (0.90, 32.13) | 2.12 | (0.18, 24.67) |
| 41–60 yrs | 1.05 | (0.52, 2.12) | 0.97 | (0.44, 2.15) | 1.65 | (0.36, 7.51) |
| 61+ yrs | 0.75 | (0.36, 1.56) | 0.59 | (0.25, 1.40) | 2.10 | (0.50, 8.88) |
| Sex (male as reference) | | | | | |
| Female | 0.64 | (0.34, 1.20) | 0.58 | (0.28, 1.18) | 1.72 | (0.36, 8.11) |
| Cardiovascular/respiratory condition (without as reference) | | | | | |
| With the condition | 2.07* | (1.02, 4.22) | 2.57* | (1.12, 5.85) | 1.06 | (0.23, 4.84) |
| With the symptom | 1.52 | (0.91, 2.53) | 1.90* | (1.08, 3.35) | 0.71 | (0.19, 2.72) |
| Cough (without cough as reference) | | | | | |
| With the symptom | 2.18* | (1.37, 3.48) | 2.05* | (1.22, 3.44) | 3.30 | (1.09, 10.03) |
| Latest viral test result (negative as reference) | | | | | |
| Positive | 2.99 | (0.83, 10.75) | 2.56 | (0.69, 9.55) | – | – |
| Wearing facemask during sampling (No as reference) | | | | | |
| Yes | 0.77 | (0.44, 1.35) | 0.71 | (0.38, 1.34) | 1.00 | (0.27, 3.65) |
| Time since last disinfection (<1 h as reference) | | | | | |
| 1–3 h | 0.58 | (0.30, 1.12) | 0.69 | (0.33, 1.44) | 0.13 | (0.02, 0.81) |
| 3–6 h | 0.77 | (0.38, 1.57) | 0.94 | (0.43, 2.06) | 0.22 | (0.03, 1.46) |
| 6–12 h | 1.61 | (0.63, 4.11) | 0.99 | (0.32, 3.03) | 3.18 | (0.36, 28.37) |
| >12 h | 0.32 | (0.06, 1.65) | 0.47 | (0.09, 2.51) | – | – |
| Number of patients in the same isolation room (1–2 patients as reference) | | | | | |
| 3 patients | 1.18 | (0.60, 2.29) | 1.01 | (0.48, 2.14) | 1.60 | (0.37, 7.00) |
| 4 patients | 1.60 | (0.84, 3.03) | 1.67 | (0.82, 3.42) | 0.89 | (0.19, 4.17) |
| 5 patients | 1.01 | (0.15, 6.73) | 1.74 | (0.22, 13.89) | – | – |

* P < 0.05.
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Fig. 2. Odds ratios of positivity rate in (A) overall, (B) surface and (C) air samples at different Ct values of the latest viral test results of the patient. Note: Grey areas show 95%CI of the ORs; red dashed line: OR = 1.0, Ct value 35 as reference).

between this study and the systematic review may be attributed to differences in volume of air collected for each sample, as this study collected 1000 L in 20 min for each air sample, while the volume of air samples reported in the systematic review ranged from 90 L to 108,000 L per sample. Intuitively, higher volume of sample may lead to higher likelihood of capturing virus fragments suspended in the air. These ultra-high-volume air samplers usually required 4 h or more to complete the air sample collection making it not suitable for this study considering the noise generated by the sampler in the patient area. The longer time it takes to collect sample, the more likely other confounding factors may be at play. However, despite the varying incidence of air sample positivity rate, the air samples collected even in rooms with negative pressure system could be positive for SARS-CoV-2 emphasizing the need for stringent infection control precautions for staff working in these areas.

Besides this, the distance of the sampling spot to the patient, air exchange rate of the ventilation system, and environmental temperature and humidity as well as patient’s clinical conditions may also make a difference in positivity rate or risk of environmental contamination. First, the location of sampling is associated with the contamination risks, as it was found that the positivity rate was higher in the spots closer to the patients, who were instructed to sit in the bed during the sampling. The viral RNA was not found in the air samples collected outside the range of the bed, including the samples collected in the middle of the room (around 2–3 m away from the patient, spot #6 in Fig. 1). The reason for negative findings at the spot #6 could be that the sample size at this spot was relatively small, or it is difficult for the virus to be carried outside a range of 2 m, especially when the patient is wearing a mask most of the time during the stay in the cubicile installed with a ventilation system. The latter explanation is supported by a systematic review of 172 observational studies that indicated a low level of positivity rate in the distance larger than 2 m (Chu et al., 2020).

Secondly, a deceasing trend of positivity rate was found through 18 °C - 24 °C inside the cubicle, with control of other variables, as the stability and infectivity of the virus might be affected by higher temperature (Biryukov et al., 2021; Rath and Kumar, 2020). Similar findings were revealed in previous laboratory experiments, which found that the half-life of the virus reduced as the temperature increased from 24 °C to 35 °C (Biryukov et al., 2020, 2021). A study using real-world data also found that the basic reproduction number ($R_0$) reduced as the temperature increased from −5 °C to 20 °C (Smith et al., 2021). Another ecological study showed the transmission rate was lower in higher temperature (>30 °C) (Raines et al., 2021). On the other hand, although there is no significant difference in positivity rate across different humidity found in this study, previous studies showed that dry environment is associated with higher stability of SARS-CoV-2. A study found that the half-life of the virus was significantly longer in 20 % RH (Relative Humidity) (24 °C compared with 60 % and 80 % RH (Biryukov et al., 2020). The dry rate of infectivity, the virus was found higher under 70 % relative humidity (RH) compared with 20 %–55 % RH; however, the temperature (within 10 °C–40 °C) had greater influences on the infectivity than humidity (within 20–70 %) (Dabisch et al., 2020). The outcome from this study is limited by small number of days with humidity higher 70 % and lower than 40 % as it was conducted in the environment with air conditioning.

Thirdly, patient characteristics including presence of fever and cough at the day of sampling, lower Ct values of latest test for respiratory tract samples, and pre-existing respiratory and/or cardiovascular conditions were associated with higher positivity rate. These findings could be used to inform the front-line clinicians in identifying patients with higher risk of environmental contamination, which could lead to transmission of the virus and cause cross-infection of the patients and the healthcare workers. Coughing is found to be associated with higher contamination level, which is plausible as SARS-CoV-2 is likely to be emitted in the air or on the surface through coughing. Similar findings were found in two studies in South Korea that symptomatic patients have longer durations of viral shedding or time until negative conversion than patients without any symptom (Noh et al., 2020; Uhm et al., 2020). Nevertheless, no study has reported the association between daily symptom presentation and the degree of environmental contamination. From the supplementary analysis for different time since disinfection (Supplementary table S1 and S4), the findings indicated that patient’s symptoms, particularly coughing, could be an indicator for higher environmental contamination risk within 3 h after disinfection even controlled for Ct value of patient’s viral test, while the degree of environmental contamination of patients who coughed and those who did not cough would reach to similar level over 3 h after disinfection with Ct value controlled. This also highlights that it is important to perform more frequent disinfection particular for patients with coughing symptoms. This study did not find time-lag effect of presence of cough or fever on environmental contamination, which is reasonable in the context of medical isolation ward setting as periodic disinfection and continuous air ventilation was performed in the wards to reduce concentration of the virus.

For Ct values of latest test for respiratory tract samples, including nasal swabs and deep throat saliva, it was found to be negatively associated with positively rate in both surface and air samples, as lower Ct values indicates a higher viral load of the patient. The likelihood of being contaminated was associated with Ct values lower than 25. This is consistent with the findings in Singapore that there were higher percentage of high-touch surface contamination among patients with Ct values lower than 25 (Chia et al., 2020). Based on this finding, additional precautions should be considered particularly for patients with Ct value lower than 25, and further study can be conducted to find out whether this is a valid cut-off for rating the infectivity of patients. As for pre-existing respiratory and/or cardiovascular conditions, patients with
these conditions were more likely to have severe conditions and symptoms (Del Sole et al., 2020; Lu et al., 2020; Tian et al., 2020; Z. Zheng et al., 2020), and the viral shedding period was likely to persist longer (S. Zheng et al., 2020); hence, they are more likely to contaminate the environment of their surroundings.

A few limitations of the study should be noted. First, this study investigated the degree of SARS-CoV-2 contamination in the isolation wards and other places in the hospital using RT-PCR test for the RNA of the virus; however, it did not test the viability or infectivity of the virus in these samples, which is scarce among published studies (Goncalves et al., 2021). Second, in sampling inside the isolation rooms, the positivity rate is associated with number of patients in the same room, but the symptoms and other characteristics of other patients were not all recorded as not all of them in the same room agreed to, or assessed to be suitable by the doctors, to participate in this study. Lastly, the finding of this study can be generalized to negative pressure isolation rooms with ventilation system, but it may underestimate the degree of air and surface contamination if it is generalized to other healthcare settings or community settings without such ventilation system and routine disinfections. We were also unable to test the transmission of the more recent omicron variants.

5. Conclusions

This study conducted daily follow-up of COVID-19 patients inside the isolation wards for environmental sampling and recording their daily status. Although the overall contamination level is low, the findings revealed that degree of air and surface contamination is much higher in the cubicle and anterooms for COVID-19 patients, and the risk for surface contamination is higher than air contamination. Timely and frequently disinfections in the key spots should be in place in daily practice. Patients with pre-existing respiratory and/or cardiovascular conditions, fever, cough and higher virus load (Ct value lower than 25) were found to have higher risk for environmental contamination. Lower environmental temperature is also associated with higher degree of contamination. Healthcare workers should be suggested to take extra precautions when stay close to the patients who have pre-existing conditions, presence of COVID-19 compatible symptoms, and low Ct values. Measures such as consistently use of curtains and installation of air cleaners should be considered for these patients.

Funding

This work is supported by Health and Medical Research Fund, Food and Health Bureau of Hong Kong SAR Government, Hong Kong, China (grant number: COVID190101).

CRediT authorship contribution statement

Kailu Wang: Conceptualization, Methodology, Investigation, Formal analysis, Funding acquisition, Writing – original draft.; Kin Fai Ho: Methodology, Resources, Funding acquisition, Writing – review & editing; Larry YT Leung: Investigation, Data curation, Project administration, Writing – review & editing; Kai Ming Chow: Methodology, Investigation, Funding acquisition, Writing – review & editing; Yuk Yam Cheung: Methodology, Investigation, Writing – review & editing; Dominic Tsang: Methodology, Funding acquisition, Writing – review & editing; Raymond WM Lai: Methodology, Funding acquisition, Writing

Fig. 3. Odds ratios of positivity rate in overall, surface and air samples at different environmental temperature and humidity. Note: Grey areas show 95 %CI of the ORs; red dashed line: OR = 1.0, 20 °C and 60 % humidity as reference. Odds ratio according to temperature: (A) overall, (B) surface and (C) air samples. Odds ratio according to humidity: (D) overall, (E) surface and (F) air samples.
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.

Acknowledgement

We would like to acknowledge the Health and Medical Research Fund in supporting this research, Prof Christopher Lai for support in conducting the research and in recruiting subjects. We would also like to thank all the research team members and all those in JC School of Public Health and Primary Care who have contributed to make this study possible. The financial support of the Centre for Health Systems and Policy Research is from The Tung’s Foundation.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ececo.2022.113740.

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