INTRODUCTION

Coronavirus disease 2019 (COVID-19) has spread worldwide, and its influence has penetrated people’s daily lives. Although COVID-19 vaccination rates have increased worldwide, fully combating COVID-19 is hindered by the appearance of more contagious new variants and the development of vaccine resistance.1 Droplets from COVID-19 patients are released into the atmosphere by breathing, speaking, coughing, and sneezing,2 and these particles are suspended for several hours by thermodynamic deformation caused by environmental factors.3 Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has been shown to survive in airborne aerosol droplets for 3 h4 or more.5,6
According to studies on the infectivity of SARS-CoV-2 attached to inanimate surfaces, the stability of the virus may vary from several hours to several days depending on the type of fomite and the surface condition. SARS-CoV-2 can survive for up to three hours in the air, and for four hours on copper surfaces, 48 h on stainless steel, 72 h on plastic surfaces, and hours to days on paper, wood, and cloth. Environmental temperature and humidity conditions also affect COVID-19 infection because the virus is inactivated at high temperature and high humidity.

Currently, most studies aiming to detect SARS-CoV-2 on surfaces and in the air have only tested for viral RNA by real-time reverse transcription-polymerase chain reaction (RT-PCR), which has produced insufficient evidence for infectivity. Infectious virus is excreted from the respiratory tract of an infected person for only 7 days, while viral RNA excretion lasts for 28 days. Detecting the infectious virus on environmental surfaces may be rare once the patient only sheds viral RNA and no longer sheds infectious SARS-CoV-2. Furthermore, few studies have confirmed the presence of viable viruses from RT-PCR-positive environmental samples.

The detection of SARS-CoV-2 RNA in environmental samples does not confirm their ability to infect humans, as opposed to SARS-CoV-2 detected through cell culture that is infectious. However, the cell culture method takes 3–4 days to cultivate and 72 h to confirm after inoculation, resulting in a minimum of 6 days for confirmation, compared to within 24 h after sampling for RT-PCR. Cell culture is not suitable for rapid response or for large sample sizes. In addition, the difficulty in obtaining a recoverable SARS-CoV-2 cell culture sample hinders its application to field investigations. In order to quickly reopen facilities used by an unspecified number of people, it is necessary to consider both certainty and efficiency. RNA detection via RT-PCR within 24 h, including pretreatment, is faster than the virus culture method that can clearly confirm whether the virus remaining in the environmental sample can cause secondary infections of people. If environmental samples tested negative for SARS-CoV-2 RNA, the facility can be safely reopened for use. Using real-time RT-PCR to quickly respond to target facilities will reduce the social costs arising from prolonged closure. Some facilities simply cannot be closed for extended periods, such as apartments, public transportation, and large hospitals. In particular, the closure of large hospitals for an extended period will lead to a shortage of medical institutions capable of treating emergency patients. Furthermore, it is necessary to check the effectiveness of disinfection through viral RNA testing to ensure the safety and health of citizens. Thus, environmental RNA detection can be a strategy to track and monitor the rate of viral spread in communities and to suggest preventive measures.

People spend more than 90% of the day indoors, and viral infections are easily transmitted and acquired, especially in crowded and poorly ventilated indoor environments. Preventing the spread of infectious diseases requires identifying the transmission route and responding appropriately. The specific transmission routes of SARS-CoV-2 are as follows. First, it is transmitted from person to person. The virus spreads through contaminated droplets and by contact. Respiratory droplets generated when an infected person coughs, sneezes, or speaks are transmitted to non-infected persons in the same space. This route can be blocked through preemptive actions based on the detection of environmental viral RNA in multi-use facilities before an outbreak occurs. In a case of environmental contamination of the virus, a facility can be closed, and disinfected and all facility users can be tested for COVID-19. The second transmission route is the spread of the virus through inanimate surface contact arising from touching droplet-coated objects with the hands and then touching the eyes, nose, or mouth. Again, this route can be blocked by testing all object surfaces for the SARS-CoV-2 virus and responding appropriately such as closing, disinfecting, ventilating, and cleaning. The third is air transmission in which aerosol particles containing viruses are widely spread in the air and thus infect non-infected persons. A non-infected person can even be infected by entering an enclosed room with inadequate ventilation from which an infected person has just exited. The virus attached to the aerosol can be captured through inhaling the air in the room by an air scanner. Transmission can then be prevented by testing for the presence of the virus and responding appropriately.

The present study has three goals. First, by conducting a long-term environmental investigation of SARS-CoV-2 RNA in numerous multi-use facilities in Seoul, we specifically identified those facilities with positive results even after disinfection and are thereby able to share the common causes leading to these positive results. Second, we aim to provide a protocol that can ensure the safety of citizens and can enable the target facility to be reopened rapidly by clearly confirming the presence of environmental contamination of the virus on surfaces and in the air. Finally, we suggest a plan to prevent the spread of cluster infections in multi-use facilities by identifying

---

**Practical Implications**

- A metropolitan-scale investigation was conducted on the environmental contamination of SARS-CoV-2 RNA over a year in Seoul.
- SARS-CoV-2 RNA was detected on the object surfaces several days after disinfection, and most of the positive samples were collected on the surfaces containing moisture in indoor environments that were not well ventilated.
- Based on testing at 231 multi-use facilities in the field, this study presented a protocol for safely reusing such facilities by confirming whether there is environmental contamination by virus RNA after disinfection.
- A preemptive investigation of environmental contamination of the virus helped to prevent the spread of the infectious disease by identifying the potential existence of asymptomatic patients.
the potential existence of any pre/asymptomatic users of the facilities through a preemptive investigation of environmental contamination of the virus.

2 | MATERIALS AND METHODS

2.1 | Study design and data collection

The population of South Korea is about 51.3 million people, and the population of Seoul is 9.7 million, accounting for about 20% of the total population. But while the area of South Korea is 16,364 km², the area of Seoul is 605 km², representing only 0.6% of the total land. Seoul is the capital and largest city of South Korea with a population density of 509 people/km². As a result, the population density of Seoul is about 32 times higher than that of the nation, which suggests far greater inter-person contact than in other regions. This highlights the importance of intensively managing Seoul to prevent the spread of COVID-19. Between January 2020, when the first COVID-19 case was recorded in South Korea, and February 2021, 89,676 persons were confirmed positive, while cumulative cases of COVID-19 in Seoul accounted for about 30% of the South Korean total (SI 1, 2). Table 1 shows that deaths have occurred, with a mortality rate of 1.79%.31

The WHO proposed a practical protocol for collecting environmental samples in hospitals and homes where COVID-19 patients have stayed.32 Based on this, we extended the range of the environmental tests to public multi-use facilities. During February-April 2020, we conducted a full investigation of such multi-use facilities (Table 2) that we could obtain consent from the owners. As no SARS-CoV-2 RNA signal was detected in any environmental samples for the first three months, only the facilities requested by the owners or multi-use facilities with cluster infections were examined after May. A cross-sectional study design was used for detecting viruses in the indoor environment in order to check the safety of the target facilities that pre/asymptomatic persons had visited from February 2020 to January 2021. The procedure for conducting this investigation is shown in Figure 1.

As shown in SI 1–4, the number of daily confirmed cases increased explosively between February and March 2020 in regions other than Seoul. According to SI 4, the daily number of confirmed cases in Seoul was between 0 and 30 before mid-August, and then subsequently rising to more than 100, with this increase being attributed to summer holidays. The onset of winter led to a further increase to more than 1,000 confirmed daily cases (SI 2–4). As the increase seen during the August holiday season revealed a possibility of an exponential increase in case numbers over the Lunar (Chinese) New Year’s holiday in February, so a preliminary inspection was needed to prevent the increase. A preemptive inspection study was carried out according to the procedure shown in Figure 2.

We selected 22 multi-use facilities that were frequent sites of group infections, such as call centers, nursing facilities, logistics centers, and homeless facilities (Table 4).

2.2 | Sampling

The surface samples included all surfaces reported as having been touched by the infected study subjects according to the epidemiological investigation and all surfaces likely to have been touched by people in general. Surface sampling complied with the “Surface sampling of COVID-19: a practical ‘how to’ protocol” of WHO,32 which has a recommended swab surface area of 25 cm². Airborne samples were collected at indoor sites where asymptomatic or pre-symptomatic carriers had visited. The survival time of SARS-CoV-2 on object surfaces is longer than in air.4 Also, as most of the

TABLE 1 COVID-19 statistics in South Korea, January 2020-February 2021

| Period     | Monthly deaths/cumulative deaths in South Korea | Monthly confirmed cases/cumulative cases in South Korea | South Korea COVID−19 death rate (%) |
|------------|-------------------------------------------------|------------------------------------------------------|-----------------------------------|
| January 2020 | 0/0                                             | 4/4                                                  | 0.00                              |
| February 2020 | 16/16                                            | 2,927/2,931                                        | 0.55                              |
| May 2020     | 146/162                                          | 6,855/9,786                                        | 1.66                              |
| April 2020   | 85/247                                           | 979/10,765                                         | 2.29                              |
| May 2020     | 22/269                                           | 703/11,468                                         | 2.35                              |
| June 2020    | 13/282                                           | 1,332/12,800                                       | 2.20                              |
| July 2020    | 19/301                                           | 1,505/14,305                                       | 2.10                              |
| August 2020  | 20/321                                           | 5,642/19,947                                       | 1.61                              |
| September 2020 | 86/407                                         | 3,847/23,794                                       | 1.71                              |
| October 2020 | 57/464                                           | 2,717/26,511                                       | 1.75                              |
| November 2020 | 62/526                                           | 7,690/34,201                                       | 1.54                              |
| December 2020 | 374/900                                        | 26,539/60,740                                      | 1.48                              |
| January 2021 | 520/1,420                                        | 17,465/78,205                                      | 1.82                              |
| February 2021 | 183/1,603                                       | 11,471/89,676                                      | 1.79                              |
droplets are attached to or sink onto surfaces by air diffusion and gravity after some hours, more swab samples were taken than air samples.

Surface samples were collected with a swab pipette (Pipette Swab Plus, 3 M, USA). Aerosol samples were taken with the MD8 air scanner (AirPort MD8, Sartorius Stedim Biotech, Germany), which is a portable and easy-to-use air sampling instrument for the collection of airborne viruses. The air scanner was equipped with a disposable gelatin membrane filter (Sartorius Stedim Biotech, Germany) to capture viruses floating in the air. The aerosol collection device was installed at a height of 1.5 m and used to take two separate samples with an air intake flow rate of 50 L/min for 20 min.

### 2.3 | Sampling transfer and processing

All samples were shipped at 4°C in cooler bags prior to transfer to a laboratory. Samples were immediately processed in biosafety level 2 or 3 (BLS-2 or BLS-3) laboratories and directly analyzed. A BSL-2 laboratory deals with agents associated with human diseases that pose a moderate health hazard. A BSL-3 laboratory typically focuses on microbes that are either indigenous or exotic, and can cause serious or potentially lethal disease through inhalation. All samples were analyzed within 24 h. Prior to RNA extraction, gelatin filters for air samples were cut out and put it in 50-ml conical tubes to which was added 16 mL buffer solution (3% BSA-0.01 M PBS). The conical tubes were vortexed and the contents dissolved in an incubator at 37°C.

### TABLE 2 | Multi-use facilities tested in Seoul following confirmed cases of COVID-19 and the number of environmental samples obtained, February 2020-January 2021

| Type of multi-use facility | Facilities No. | Surface samples (positives, %) | Air samples (positives) | Total samples (positives) | Positive/Total (%) |
|---------------------------|----------------|-----------------|-----------------|-----------------|------------------|
| Restaurant                | 51             | 367 (0)         | 0 (0)           | 367 (0)         | —                |
| Hospital                  | 33             | 175 (0)         | 0 (0)           | 175 (0)         | —                |
| Business site             | 32             | 138 (5, 3.62%)  | 1 (0)           | 139 (5)         | 3.60             |
| Public transportation     | 31             | 468 (1, 0.21%)  | 32 (0)          | 500 (1)         | 0.20             |
| Pharmacy                  | 25             | 51 (0)          | 0 (0)           | 51 (0)          | —                |
| Mart                      | 20             | 105 (0)         | 4 (0)           | 109 (0)         | —                |
| Traditional market        | 10             | 92 (0)          | 0 (0)           | 92 (0)          | —                |
| Convenience store         | 7              | 20 (0)          | 0 (0)           | 20 (0)          | —                |
| Hotel                     | 5              | 60 (0)          | 4 (0)           | 64 (0)          | —                |
| Public institution        | 5              | 21 (0)          | 3 (0)           | 24 (0)          | —                |
| Department store          | 4              | 82 (0)          | 7 (0)           | 89 (0)          | —                |
| Religious facilities      | 2              | 53 (0)          | 3 (0)           | 56 (0)          | —                |
| Apartments                | 1              | 51 (4, 7.84%)   | 0 (0)           | 51 (4)          | 7.84             |
| Others                    | 5              | 32 (0)          | 0 (0)           | 32 (0)          | —                |
| Total                     | 231            | 1,715 (10, 0.58%) | 54 (0)       | 1,769 (10)      | 0.57             |

aThe SARS-CoV-2 RNA was detected in the staff lounge of the D subway station, which was included as public transportation, but it was a restricted area that was only available to employees and inaccessible to public transportation users.
Surface samples collected by swab included buffer peptone water broth (Pipette Swab Plus®, 3 M, USA). Before RT-PCR, buffer solutions of swab samples were vortexed for 1 min. 35 Samples (270 ul) were put into 270 ul of lysis buffer and reacted at room temperature for 10 min before 500 ul was added to the processing cartridge, and extracted with a MagNA Pure 96 (Roche, Penzberg, Germany) machine.

2.4 | Laboratory methods

Virus detection was carried out by analyzing the presence of viral RNA with real-time PCR. We tested the samples with a RT-PCR kit (PowerChek™ 2019-nCoV Real-time PCR Kit; Kogenebiotech, South Korea) targeting the E (envelope) gene and the RdRp (RNA-dependent RNA polymerase) gene, as described by Corman et al, Hong et al and KCDC.11,13,14,44,45 PCR mixtures were prepared separately for the E and RdRp genes. Thermal cycling conditions included reverse transcription at 50°C for 300 min, an initial denaturation at 95°C for 10 min, followed by 40 cycles of 95°C for 15 s, and 60°C for 1 min.

3 | RESULTS

3.1 | Cases of SARS-CoV-2 RNA detection even after disinfection

The public-use facilities inspected included 51 restaurants, 33 hospitals, 32 business sites, including call centers and offices, 31 public transportation areas, 25 pharmacies, and 20 marts (Table 2). During the one-year study period, 231 multi/public-use facilities were investigated and 1,769 environmental samples were taken (Table 2). All facilities were disinfected using disinfectants certified by the South Korea Centers for Disease Control and Prevention (KCDC), including chlorine compounds, alcohol, benzalkonium chloride, hydrogen peroxide, and chloroxylenol, and the effective concentration and surface contact times were in accordance with KCDC’s guidelines and WHO’s Cleaning and disinfection guidelines.36,37 The air-capture samples were tested, and all of 54 samples were negative, which confirmed the 100% effectiveness of disinfection in eliminating SARS-CoV-2 from air samples. (Table 2). A total of 1,715 surface swab samples were tested, and 10 samples were positive. However, 0.58% of the surface samples
returned a positive detection result for viral RNA, even after disinfection (Table 2). Ct values of all positive samples are shown in Figure 3. Cases (1–4) of SARS-CoV-2 RNA detection even after disinfection are specifically described (Table 3).

### 3.1.1 | Case 1: Call center A

This facility was a telemarketing business site with 14 infected staff after May 26. After the initial infection, the facility was disinfected immediately and the swab samples were taken and tested two days later. This office was equipped with monitors and phones, which were installed on partitioned desks, and the employees speak on phones with telephone headsets, which results in a high possibility of droplet deposition onto office equipment. In particular, even at the time of sampling, the sponge microphone section of the headset on which SARS-CoV-2 RNA was detected remained moist until sampling.

### 3.1.2 | Case 2: Call center B

Among 20 employees, the first COVID-19 patient at this center was confirmed on September 4, and testing of the remaining 19 identified as contacted persons revealed 16 infected people. The office was disinfected immediately on September 4, and surface samples were taken on September 5. SARS-CoV-2 RNA was detected on the door handle and the filter surface of the air conditioner (Table 3). The door handle was a typical object used by most in the office, and the air conditioner’s role in circulating air was highly likely to have spread the patients’ droplets.

### 3.1.3 | Case 3: Apartment C

Although all residents of the building used a common elevator and doorways, COVID-19–infected persons were found in only one line of the apartments in a co-residential area. As the routes of infection were difficult to clearly define in this case, environmental samples were taken and tested. Swabs from the outer surfaces of the dwellings, such as elevators and front doors, were collected from 23 objects, while 28 surface samples were collected from within households, including vents and drains. Since the vents and drains of the building where the confirmed cases occurred were arranged in a straight line, environmental samples from these were intensively examined. Four (7.8%) among the 51 surfaces were tested positive (Table 3). The common characteristic of the three apartments was positive test results only in the bathroom floor and sink drains. The bathrooms of these apartments were windowless with and were only ventilated through a single extraction fan, so they were probably more humid than bathrooms with both windows and full ventilation systems that included filters. As the unknown epidemiology of the infected people living in the building was unclear, and no SARS-CoV-2 RNA was detected in the ventilation system of another household in the same line, it is worth considering the possibility of infection occurring through the drain.

### 3.1.4 | Case 4: Subway station D

This transfer subway station connecting 2 different subway lines with an average daily usage of about 30,000 people is located in a downtown area connected to department stores and a large market. A staff member working at this subway station became infected with COVID-19, followed by seven other staff who worked together. Inspection and testing of the concourse and platform were conducted urgently on September 25 due to the station’s very high patronage. In addition, we checked a staff rest lounge commonly used by the positive workers, and took four environmental air samples: one each from the staff lounge, station office, concourse, and platform. All were negative.

The 30 object surfaces tested on the concourse including 10 vents, stair handles, escalator handles, turnstiles, elevators, and chairs. The 12 object surfaces tested on the platform included three vents, vending machines, chairs, and elevators. All these samples were negative. Of the 78 objects extensively sampled in the staff lounge, including closets, air purifiers, washing machines, faucets, vents, shoe racks, and towels, SARS-CoV-2 RNA was detected on a towel hanging in the windowless shower room in the lounge (Table 3) and the Ct values of RdRP and an E gene were 34.6 and 37.2, respectively (Figure 3). On September 27, two days after initial disinfection and closure, the surface of the objects was sampled (Table 3). Notably, this towel was still wet when collected for testing. Following our immediate notification of the positive result, the lounge was disinfected twice more and was kept closed. On September 29, 24 surface samples, including the towel in the shower room, were re-examined and all were negative.

### 3.2 | Cases of SARS-CoV-2 RNA detection in preemptive investigations.

The daily confirmed cases in Korea surpassed 1,000 and in Seoul surpassed 500 in mid-December 2020 (SI 3–4). This rapid increase in the number of confirmed cases necessitated a preemptive response in early January in preparation for the February holiday. For preemptive inspections, as shown in Table 4, seven types of facility where group infections frequently occurred were selected, and 22 facilities were inspected between January and February 2021.

Of the 643 tested environmental samples, five from two homeless facilities were positive. Air samples were captured from various locations within the facilities, but all were negative. All positive reactions came from surface samples, and these are described individually.
**TABLE 3** Specific cases in which positive SARS-CoV-2 RNA was detected in indoor environments after disinfection between February 2020 and January 2021 in Seoul

| Case No. | Types of public-use facility | Date of the first positive result / case no. | Date of disinfection | Date of sampling | Positive surface objects | Negative surface objects | No. of total samples |
|----------|------------------------------|---------------------------------------------|----------------------|------------------|--------------------------|--------------------------|----------------------|
| 1        | Call center A                | May 28 /14                                  | May 28               | June 1           | Headset, phone (2)       | Elevator button (7), phone (10), door, office supplier (6), restroom (2) | 29                   |
|          |                              |                                             |                      |                  | 3 (10.3%)                | 26 (89.7%)               |                      |
| 2        | Call center B                | Sep. 4/16                                   | Sep. 4               | Sep. 5           | Door handle, air conditioner | Toilet (2), toilet door handle (4), air conditioner, microwave, elevator handle, elevator button (3), building door handle | 15                   |
|          |                              |                                             |                      |                  | 2 (13.3%)                | 13 (86.7%)               |                      |
| 3        | Apartment C                  | Sep. 10/3                                   | Sep. 10              | Sep. 12          | Toilet floor drain (2), toilet sink drain (2) | Elevator button (21), Elevator handle, common door, door handle (4), kitchen vent (4), bathroom vent (4), toilet sink drain (3), toilet floor drain (2), bathtub drain (2), toilet (5) | 51                   |
|          |                              |                                             |                      |                  | 4 (7.8%)                  | 47 (92.2%)               |                      |
| 4        | Staff Lounge of Subway Station D | Sep. 25/8                                | Sep. 25              | Sep. 27          | Towel                  | Closet handles (22), table (2), first-aid kit, phone, remote controller, air purifier (2), fan, shoe closet, switch (3), door handle (3), refrigerator (2), water purifier, microwave, storage box handle, electric pot, faucet (5), spoon basket, detergent container (2), trash can, washing machines (2), hanger, shoes (17), fire extinguisher, ventilation system (4) | 78                   |
|          |                              |                                             |                      |                  | 1 (1.3%)                  | 77 (98.7%)               |                      |
3.2.1 | Case 5: Refuge for the homeless E

There were no confirmed cases in this homeless shelter. Mechanical ventilation and disinfection had been performed each morning for 30 min. When we visited in the afternoon on February 3, homeless people had used the facility until the morning of that day. As a result of examining the surfaces of objects in the sleeping room, the restrooms, and the shower room, all positive-testing objects were of the same type (Table 5). Of 25 tested objects, the four positives were all on blankets. They were folded, and we spread them out and examined the inside. As soon as we received the results, the facility was notified and was disinfected after closure, and COVID-19 testing was recommended to the facility users.

3.2.2 | Case 6: Refuge for the homeless F

A preemptive visit was planned in early January, and the target facilities were visited in sequence. When we arrived at this facility to collect environmental specimens on February 6, we received the news that a confirmed case had occurred on January 25. But all facilities were still being used except for the one sleeping room at that time. This case was classified as a preemptive test as originally planned because the purpose was not to examine the movement of the confirmed person but to test the entire facility in use. The entire building, including kitchen, dining room, sleeping room, shower room, toilet, office, and affiliated hospital, was examined, and in particular, the sleeping room where the confirmed case had slept was intensively examined. The sleeping room had been permanently closed for all 12 days between January 25 and February 6 following disinfection. This building did not have individual room heating controls but used a central heating system, so that the heating continued even in the closed sleeping room during the 12-day period. SARS-CoV-2 RNA was detected with RdRp 35.7, and E gene 34.9 (Figure 4), on a folded blanket (Figure 5) in the sleeping room.

4 | DISCUSSION

After all the facilities visited by confirmed COVID carriers had been disinfected, 54 air samples and 1,715 surface samples, total 1,769, were taken (Table 2). At the 22 facilities at which preemptive investigations were performed, 61 air samples and 582 object surfaces samples, total 643, were taken (Table 4). None of these air samples returned a positive result. Previous research results have shown that air samples have a higher positive rate than surface samples in a room with an infected person, resulting in a higher probability of transmission by aerosol than by surface contact when in the same room with the COVID-19 patient. However, we obtained different study results for tested indoor environments after the confirmed cases had left. Our results suggest a low risk of infection from the air for a certain period of time after the infected individual leaves. The droplets mixed with SARS-CoV-2 are airborne for a finite amount of time but then sink onto surfaces by gravity and dry up.

Since 0.58% of the surface samples remained positive even after disinfection as above, note that this is a study result (Table 2), there is value in trying to identify any commonality among these positive-testing surfaces. All four positive surface samples were drains in Apartment case C, and the drains were located in windowless bathrooms. Drains are usually contaminated and wet environments. The virus RNA at Subway Station D was detected in the windowless staff shower room. Even though this shower room was disinfected and samples were taken two days later, the towel hung on a hanger was still wet. The C and D locations were both windowless bathrooms with no natural ventilation. In the case of call center A, RNA was detected two days later after disinfection in the sponge part of the headset microphone for phone calls, and this porous material only dries after an extended period (Table 4). Studies have shown that SARS-CoV-2 is more stable on a smooth surface than on a porous surface, and it is more stable in a dry environment. Biryukov et al reported that the SARS-CoV-2 of viabilities and airborne survival times expected at lower humidity levels. Nevertheless, RNA was detected even after disinfection on the wet headset sponge, the four drains, and the wet towel (Table 3).

When disinfecting contaminated surfaces, it is necessary to keep the contact times, which are times during which they must be visibly wet. If RNA is detected on the surface of a moisture object even a few days after disinfection, it is difficult to confirm that it has been wet by the disinfectant. The detection of RNA indicates the possibility that the disinfection is incapable of destroying RNA because the concentration of the disinfectant is diluted with the moisture in the

| Type of facility          | Facilities No. | Surface samples (positives, %) | Air samples (positives) | Total samples (positives) | Positive/total (%) |
|---------------------------|----------------|--------------------------------|-------------------------|---------------------------|-------------------|
| Refuge for the homeless   | 7              | 234 (5, 2.14%)                 | 31 (0)                  | 265 (5)                   | 1.89              |
| Nursing home              | 3              | 55 (0)                         | 4 (0)                   | 59 (0)                    | –                 |
| Religious facilities      | 3              | 71 (0)                         | 6 (0)                   | 77 (0)                    | –                 |
| Restaurant for workers    | 3              | 50 (0)                         | 5 (0)                   | 55 (0)                    | –                 |
| Call center               | 2              | 54 (0)                         | 4 (0)                   | 58 (0)                    | –                 |
| Logistics center          | 2              | 38 (0)                         | 2 (0)                   | 40 (0)                    | –                 |
| Facilities for disabled persons | 2               | 80 (0)                         | 9 (0)                   | 89 (0)                    | –                 |
| Total                     | 22             | 582 (5, 0.86%)                 | 61 (0)                  | 643 (5)                   | 0.78              |
object. This suggests the need to adopt an appropriate disinfection and cleaning protocol according to the type of objects rather than uniformly disinfecting the space when environmental contamination of the virus occurs in the indoor environment. Warish et al detected SARS-CoV-2 RNA in wastewater even after 18–25 days or more.°

Since domestic sewage may remain stagnant in the U-pipes of the drainage system, the disinfectant needs to be sprayed inside the drain. Textile products such as towels in the bathroom need to be dried and washed immediately after use.

All five positive test results from the preemptive examination were folded blankets. As it is in direct contact with the body, such bedding is more likely to contain accumulated body secretions than other objects. The detection of RNA in the blanket (Figure 5) stored in a closed room for 12 days reveals the absence of any washing and drying process, and the inner part of the folded blanket retained environmental contamination of the virus RNA. Therefore, we strongly recommend that such bedding is washed frequently and then spread out to dry in a well-ventilated and sunny place rather than merely being folded up immediately after use.

Following the positive COVID-19 test results at E and F homeless facilities, all people using these facilities were tested for COVID-19. This procedure helped to prevent the spread of infectious diseases through follow-up management such as quarantine of infected persons, closure of facilities, and disinfection. Mainly, testing for COVID-19 can be performed when an epidemiological investigation reveals that people have been in contact with a confirmed person, or if an infection is suspected when symptoms are present and the patient undergoes voluntary testing. Human testing cannot be forced without justifiable reasons. Reducing the spread of infectious diseases requires preemptive investigation to identify asymptomatic or pre-symptomatic persons in advance and take action. If SARS-CoV-2 is detected in the indoor environment of a target building such as those identified as the types of facility susceptible to many infections, such as the preemptive tests of this study (Figure 2), these positive results will greatly assist quarantine authorities in encouraging all facility users to get a COVID-19 test. Such procedure promises to reduce the number of infected people through follow-up management such as quarantine of infected people, closure of facilities, and disinfection.

With the ongoing potential for outbreaks of novel COVID-19 viruses, the present one-year investigation at various real sites will assist in developing a clear protocol for the management of

### Table 5: SARS-CoV-2–positive samples found in indoor environments through preliminary examinations before outbreaks of confirmed cases in Seoul, January-February 2021

| Case No. | Type of facility       | Date of Sampling | Kinds of objects (No.) | Negative samples | Location of air samples | No. of total lounge | No. of positives |
|----------|------------------------|------------------|------------------------|------------------|-------------------------|---------------------|------------------|
| 5        | Refuge for the homeless E | February 3, 2021 | Blanket (4)            | Standalone air purifier (1), door handle (1), drain (3), toilet (3), shower (4), toilet sink (1), chair (1), light switch (1), bedding (1), vent (1), toilet mirror (1) | Protective space (1), lounge (1), emergency shelter (1) | 25 | 4 |
| 6        | Refuge for the homeless F | Feb-6-2021       | Blanket (1)            | Drain (3), faucet (3), cooking table (1), refrigerator (2), lounge locker (2), lounge furniture (1), water purifier (3), table (3), chair (7), table partition (1), vending machine (1), front door (1), toilet sink (7), toilet (14), shower (6), mattress (4), sleeping room locker (9), blanket (2), wall (2), bag (2), TV (1), home appliance (1), door (2), water bottle (1), copy machine (1), hand sanitizer (1), light switch (1), closet (3), bookshelf (1), hairdryer (1), vacuum cleaner (1), lounge furniture (1), lounge locker (2) | Kitchen (1), dining room (1), room (3), library (1), staff lounge (1), shower room (1), workshop, office (1), office (1) medical room (1) | 102 | 1 |
indoor environments. Although environmental contamination of viral RNA may not directly cause infection, indoor spaces can be declared safe if such viral RNA signal is not detected. Although frequent disinfection will be effective in inactivating viruses, the risks associated with surface disinfection in public places should be considered. Regular disinfection of surfaces reduces the diversity of the microbiome and increases the diversity of bacterial resistance genes. CDC recommends disinfecting surfaces in facilities only after a person with suspected or confirmed COVID-19 enters the facility. Therefore, it is necessary to find a balance between the SARS-CoV-2 risk and the human risk of the disinfectant. The protocol presented in Figure 1 is an alternative to frequent disinfection. The disinfection method in the facility visited by the infected person should be appropriately adopted according to the characteristics of the surface of fomites. The disinfection effect can be checked by detecting the RNA signal, and the human effect of disinfectants can be reduced by minimizing the number of disinfection incidences. In addition, facilities in which RNA signals are not detected can be reopened faster. This protocol (Figure 1) can contribute to the rapid normalization of essential facilities such as daycare centers, hospitals, and public transportation, and can also help with local economic problems for related restaurant and cafe businesses.

4.1 Limitation

According to Alicia et al, the success rate of detecting SARS-CoV-2 increases if the air suction flow rate is increased in a space with a COVID-19 patient. Since this field study was conducted after the cases had been confirmed, the effects of temperature and humidity conditions and of air intake flow rate could not be investigated as a laboratory study would allow.

The RT-PCR method was chosen rather than culture that can clearly confirm the infectivity of the virus because this study aimed to secure rapid safety against infectious diseases in a huge city. The detection of a virus RNA signal does not necessarily indicate infection. However, Joshua L. Santarpia et al confirmed potential infectivity by observing SARS-CoV-2 replication in cell cultures of samples with a Ct value of <36.6 collected from the room of an infected patient. One of the target genes selected in this study is the same as the E gene selected in Santarpia et al. After disinfection, 7 out of 10 positive reactions had Ct values <36.5 (Figure 3). All positive results

---

**Figure 4** RdRP and E gene Ct values of positive surface samples, which were captured preemptively in multi-use facilities between January and February 2021 in Seoul

**Figure 5** Photograph of swabbing the bedding, which is an object surface sample of Case 6. A preemptive test resulted in a positive test at a shelter for the homeless on February 6, 2021. The sleeping room had been closed for 12 days after disinfection due to a confirmed case on January 25, 2021, but SARS-CoV-2 RNA was detected in the folded blanket in the room on February 6, 2021.
of preemptive investigations showed Ct values <36.5 (Figure 4). Another study in which SARS-CoV-2 was cultured on cotton and polyester demonstrated that the virus could not survive after the first day.12 In Case 6, the viral RNA was detected even after 12 days in a blanket, but since survival is unknown, additional research on infectivity is necessary.

5 | CONCLUSION

For 13 months, various multi-use facilities in large cities were investigated by dividing into post-outbreak and pre-inspection. This study method enabled cases to be confirmed (Table 3) where a positive reaction occurred even after disinfection. The common environmental feature was indoor spaces where not an easily ventilated, status, and object surfaces remained wet at the time of sampling. It is possible that not all of the viral RNA is destroyed by disinfecting such wet objects. When disinfecting a wet object, it is judged that it is necessary to increase the concentration of the disinfectant or additionally disinfect. However, since excessive disinfection can be harmful to the human body, disinfection methods should be appropriately selected and applied according to object type. As a result of preemptive investigations, SARS-CoV-2 RNA was detected after 12 days in a folded, unwashed blanket. Environmental contamination was identified inside the multi-use facility, and a human body examination was performed after disinfection. A preemptive investigation to identify any environmental contamination of the virus in the building before the infected patient is revealed by an epidemiological investigation enabled the spread of the infectious disease to be prevented by identifying a potential existence of asymptomatic patients in advance. Based on testing at 231 multi-use facilities, this study presented a protocol (Figure 1) for safely reopening multi-use facilities by confirming whether there is environmental contamination by virus RNA after disinfection. In combination with the preemptive investigation (Figure 2), the overall study results will assist in the development of plans to properly respond to novel infectious diseases and COVID-19.

ACKNOWLEDGMENTS

This research was supported by the Seoul Metropolitan Government. Seoul Metropolitan Government Research Institute of Public Health and Environment is one of the affiliated offices of the Seoul Metropolitan Government. The authors thank Juhee Hong, Hojun Rhee, Jinson Park Byungchul Min, and Deukhyun Yoo who helped collect the original data.

CONFLICT OF INTEREST

The authors declare no conflict of interests.

AUTHOR CONTRIBUTION

Minjeong Seo, Hakmyeong Lim, Myungkyu Park, Gwangtae Ha, Seungmi Kwon, Jinho Shin, and Jaein Lee involved in conceptualization of study and study design. Minjeong Seo, Hakmyeong Lim, Myungkyu Park, Gwangtae Ha, and Seungmi Kwon investigated and collected data. Seungmi Kwon, Jinho Shin, Gwangtae Ha, Younghee Oh, Yongseung Shin, and Minjeong Seo involved in project administration. Seungmi Kwon, Jinho Shin, Youngok Hwang, Younghee Oh, Yongseung Shin, and Minjeong Seo involved in supervision. Jaein Lee and Youngok Hwang analyzed data. Minjeong Seo and Hakmyeong Lim involved in visualization. Minjeong Seo wrote this original draft. Minjeong Seo, Hakmyeong Lim, and Myungkyu Park involved in manuscript revision.

PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1111/ina.12959.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Minjeong Seo https://orcid.org/0000-0003-4974-9910
Hakmyeong Lim https://orcid.org/0000-0003-3260-6974
Myungkyu Park https://orcid.org/0000-0002-1672-3460
Gwangtae Ha https://orcid.org/0000-0001-9748-1936
Seungmi Kwon https://orcid.org/0000-0001-8052-9980
Jinho Shin https://orcid.org/0000-0002-0994-971X
Jaein Lee https://orcid.org/0000-0003-3063-4605
Youngok Hwang https://orcid.org/0000-0002-4814-4850
Yongseung Shin https://orcid.org/0000-0002-3985-0366

REFERENCES

1. Aschwanden C. Five reasons why COVID herd immunity is probably impossible. Nature. 2021;591(7851):520-522. https://www.nature.com/articles/d41586-021-00728-2
2. Allen J, Marr L. Recognizing and controlling airborne transmission of SARS-CoV-2 in indoor environments. Indoor Air. 2020;30:557-558. doi:10.1111/ina.12697
3. Teresa M, Rosa MP, Bosch A, et al. Tracing surface and airborne SARS-CoV-2 RNA inside public buses and subway trains. Environ Int. 2021;147:106326. doi:10.1016/j.envint.2020.106326
4. van Doremalen N, Bushmaker T, Morris DH, et al. Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. N Engl J Med. 2020;382:1564-1567.
5. Fears AC, Klimstra WB, Duprex P, Hartman A, et al. Comparative dynamic aerosol efficiencies of three emergent coronaviruses and the unusual persistence of SARS-CoV-2 in aerosol suspensions. medRxiv; 2020. doi:10.1101/2020.04.13.20063784
6. Moriarty LF, Plucinski MM, Marston BJ, et al. Public health responses to COVID-19 outbreaks on cruise ships – Worldwide, February–March 2020. MMWR Morb Mortal Wkly Rep. 2020;69:347-352. doi:10.15585/mmwr.mm6912e3
7. Vicente VA, Lustosa BPR, Grissola ME, et al. Environmental detection of SARS-CoV-2 Virus RNA in health facilities in Brazil and a systematic review on contamination sources. Int J Environ Res Public Health. 2021;18:3824. doi:10.3390/ijerph18073824
8. Kampf G, Todt D, Pfaender S, Steinmann E. Persistence of coronaviruses on inanimate surfaces and their inactivation with bio- cidal agents. J Hosp Infect. 2020;104:246-251. doi:10.1016/j.jhin.2020.01.022
exposure to environmental pollutants. *J Exp Sci Environl Epidemiol*. 2001;11(3):231-252. doi:10.1038/sj.jea.7500165

44. Hong KH, Lee SW, Kin TS, et al. Guidelines for laboratory diagnosis of coronavirus disease 2019 (COVID-19) in Korea. *Annal Laborat Med*. 2020;40(5):351-360. doi:10.3343/alm.2020.40.5.351

45. Corman VM, Landt O, Kaiser M, et al. Detection of 2019 novel coronavirus (2019-nCoV) by real-time RT-PCR. *Euro Surveill*. 2020;25:2000045.

46. Centers for Disease Control and Prevention. Quick Learn Lesson. Recognizing the Biosafety Levels. https://www.cdc.gov/training/quicklearns/biosafety/

47. Eslami H, Jalili M. The role of environmental factors to transmission of SARS-CoV-2 (COVID-19). *AMB Express*. 2020;10:1-8. doi:10.1186/s13568-020-01028-0.

**SUPPORTING INFORMATION**

Additional supporting information may be found in the online version of the article at the publisher’s website.

**How to cite this article:** Seo M, Lim H, Park M, et al. Field study of the indoor environments for preventing the spread of the SARS-CoV-2 in Seoul. *Indoor Air*. 2022;32:e12959. doi:10.1111/ina.12959