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Identifying behavior of long-distance virus transmission and mitigation performance from a COVID-19 outbreak of a daycare center

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ABSTRACT

During the last two years, hundreds of millions of people in the world have been infected with SARS-CoV-2 due to recurrent waves and closed spaces. Daycare centers are critical infrastructures that cannot be replaced, even during the COVID-19 period. However, the existing settings in daycare centers may pose risks of inevitable close contact between teachers and children, as well as fomite and airborne transmission during care hours. Therefore, reinforced mitigation strategies have been applied in daycare centers to reduce potential indoor virus transfer in many countries. However, numerous outbreaks of COVID-19 have been reported in daycare centers. Therefore, in this study, researchers focused on the risk and behavior of long-distance virus transmission based on the detected viruses on air purifier filter sampling in a daycare center outbreak in Korea. Various experiments of possible situations were conducted in nursing rooms based on field interviews. The experiments monitored the long-distance transmission behavior of aerosol-sized particles and visualized particle behavior at the daycare center. The results of this study revealed that long-distance virus transmission is possible under the current settings in the daycare center, and flush-out can be an important countermeasure with reinforced ventilation methods to prevent potential airborne spread in the daycare center. The results of air purifiers represented that air purifiers should be properly installed and operated in the daycare center to prevent airborne virus spread by airflow during occupied hours. The findings of this study will contribute to the understanding of airborne virus risk and the development of customized virus measures for daycare centers.

1. Introduction

After the pandemic, 307 million people were infected, and 5.5 million people died due to the SARS-CoV-2 viruses. As of January 10th, 2022, the number of daily COVID-19 cases worldwide was 1,851,334, which was a rebound from the numbers reported in October 2021 (Worldometer, 2022). In Korea, recently, more than 3000 new patients with COVID-19 have been reported since November 2021 (KOSIS COVID-19 Status, 2021), and the social distancing system was strengthened at level 4 in the metropolitan area (MOHW, 2021a). In many types of buildings, daycare centers are in charge of a significant part of the infrastructure (CDC and Science Brief, 2021). Therefore, during the COVID-19 pandemic, daycare centers struggled to stay open and protect children from infectious viruses while providing essential services for childcare. However, the continuing COVID-19 outbreaks in daycare centers made facility officials and parents weary with substantial burdens.

To date, three primary routes of SARS-CoV-2 infection have dominated virus transfer: contact and droplet transmission, fomite transmission, and airborne transmission (WHO, 2020a). Contact and droplet transmission refers to SARS-CoV-2 virus transmission through direct or indirect contact with bodily secretions (e.g., saliva, respiratory droplets) discharged from an infected person within a short-range (Medicine, 2020; Leung, 2021; WHO and Coronavirus disease (COVID-19), 2020). Respiratory droplet transmission can occur when people closely contact an infected person within 1 m (WHO, 2020a). This is the most common route of virus transmission. Fomite transmission represents an indirect infection through touching or contacting surfaces contaminated by an infected person. Previous papers found viruses on object surfaces in field samples of places where infected patients had been (Chia et al., 2020; Razzini et al., 2020). However, there is still an argument about the possibility of this transmission route. Marsalek (2021) pointed out that

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Airborne virus infection is a transmission route through aerosol-sized droplet nuclei containing viruses from the carrier. Aerosols are typically equal to or less than 5 μm in diameter, and they are exhaled through normal breathing and conversation (WHO, 2014). In SARS-CoV-2 transmission, viruses containing aerosols can float in the air and be delivered over long distances (WHO, 2014; Yu et al., 2021; Moraw ska et al., 2020). Thereby, vulnerable people can become infected by inhaling aerosols if they are exposed to enough viruses to cause infection (WHO, 2020a). Even though there have been many discussions on infectivity and long-range transmission of aerosols in the scientific community, the World Health Organization (WHO) has acknowledged the potential of airborne transmissions, such as in poorly ventilated and/or crowded indoor environments (WHO, 2021). Similarly, the U.S. Centers for Disease Control and Prevention (CDC) recognized that the SARS-CoV-2 virus could be transmitted across a six-feet distance from infected people (CDC and Scientific Brief, 2021).

Recent studies pointed out the impact of various air pollutants on airborne transmission and the fatality rates of COVID-19. In a review study, Marques and Domingo (Marques and Domingo, 2022) found that long-term exposure to potential air pollutants might give rise to a negative impact on the severity and the recovery period of the SARS-CoV-2 infectees. This study confirmed a significant relationship between exposure to environmental air pollutants and the incidence and fatality of the SARS-CoV-2 based on the scientific evidence from previous articles. Kim et al. (2021) discussed the potential risk of Particulate Matter (PM) as a container of infectious diseases (e.g., COVID-19). This study represented a suggestion that the national codes and standards should consider the monitoring of indoor air pollutants and control guidelines for better indoor air quality controls in multi-use facilities. Maleki et al. (2021) conducted a systematic review of 167 studies (19 articles selected) to identify the association between PM and SARS-CoV-2 transmission. The researchers concluded that the positive role of PM was verified to deliver viruses and promote airborne dispersion of COVID-19. Therefore, the risk of airborne transmission should be carefully controlled, especially in daycare centers, to protect young children.

Regarding outbreaks in daycare centers, there are a lot of direct contacts with nursing teachers and the potential chances of fomite infection (e.g., toys, books). Airborne transmission is possible since nursing teachers and children spend several hours in closed spaces every day. For example, from January to March 2021 in Korea, there were 36 cluster outbreaks in daycare centers and kindergartens, with a total of 635 (n = 17.6 cases/place) confirmed cases. According to health authorities (KDCPA, 2021a), the risk factors in daycare centers and kindergartens were the attendance of symptomatic patients, many close contact activities (e.g., meals and play activities), and insufficient wearing of masks and indoor ventilation. Therefore, health authorities have recommended no school attendance or prompt virus tests of people suspected of being infected (e.g., fever, respiratory symptoms, etc.) to prevent cluster infection. However, despite many efforts, cluster outbreaks have been continuously reported in daycare centers. Notably, the cluster infection in Sejong, Korea, provided indirect evidence of potential airborne virus transmission in the daycare centers. In the R-daycare center, viruses were found on the air purifier prefilters in sampling tests, including samples from a patient-free nursing room (KDCPA, 2021b). Further, in the epidemiological investigation, there were no identified routes through direct contacts between infected persons for inter-room transmission.

Therefore, the objective of this study is to investigate how the SARS-CoV-2 virus can be transferred from potential infectious sources to air purifiers in nursing rooms at the R-daycare center and identify the mitigation performance under the current operation methods. Since apartments are the most common residential type in Korea, the investigation of airborne virus transmission in the daycare center of the apartment complex can be used to supplement the weakness of the COVID-19 guides from health authorities or operation methods of daycare centers during the pandemic. The transmission behavior of virus-like substances was monitored based on the ventilation conditions in nursing rooms. The effects of air purifier installation methods were assessed through a laser visualization experiment. Finally, mitigation strategies were proposed to reduce COVID-19 risk in daycare centers.

2. Virus transmission and controls in daycare centers

2.1. Infection controls in daycare centers

During the COVID-19 pandemic, virus transmission and mitigation strategies for daycare centers have been studied by numerous researchers and entities (Kim et al., 2021; Lopez et al., 2020; MOHW, 2021b; CDC, 2021a; Cohen et al., 2020; CDC, 2021b). In Korea, the Ministry of Health and Welfare (MOHW) has guided and updated responses to COVID-19 for daycare centers. The latest guidelines (MOHW, 2021b; MOHW, 2021c) require that daycare centers designate staff in charge of infectious disease control and perform prevention activities of virus infection. Mitigation activities are also recommended for daycare centers. For example, cleaning the main spaces, air filtering, and frequent natural ventilation are encouraged during childcare hours to eliminate airborne contaminants. The direct wind from heating and cooling systems and the recirculation of indoor air should be minimized. To prevent close contact transmission, the spaces in daycare centers should be disinfected every day, and educational items and stuff (e.g., toys, books) with which children and childcare staff frequently come into contact should be sterilized at least twice a day. During the childcare program, direct contact with children, staff, or visitors is not recommended. Indoor and outdoor programs are expected to maintain at least one person per 4 m² and the quarantine guidelines (MOHW, 2021b; MOHW, 2021c).

Table 1 describes the COVID-19 reopening measures for daycare centers from the health authorities and previous literature (MOHW, 2021b; CDC, 2021a; WHO Coronavirus disease (COVID-19): Schools, 2020; WHO, 2020b; Ehrhardt et al., 2020). In many countries, infectious disease controls to prevent SARS-CoV-2 have been stipulated for daycare centers and schools. The WHO has provided the prevention and control measures to support preparation for COVID-19 and to ensure the indoor safety of students and teachers at schools (WHO Coronavirus disease (COVID-19): Schools, 2020; WHO, 2020b). The CDC has updated its “Guidance for Operating Child Care Programs during COVID-19” to supplement the legal systems (e.g., laws, rules, and regulations) of federal and regional public health and safety. This includes COVID-19 prevention measures and guidance for child care providers (CDC, 2021b; CDC, 2021b). The federal state of Baden-Württemberg in Germany provided preventive measures to stay healthy against the SARS-CoV-2 virus when reopening schools and childcare facilities in 2020 (Ehrhardt et al., 2020). Key points of the above-mentioned control measures are early screening of potential patients, contaminant removal and behavioral prevention methods, occupant density controls, and control measures for primary transmission routes (e.g., close, fomite, and airborne transmission).

2.2. Reopening and COVID-19 outbreaks in daycare centers

Globally, reopening schools and childcare facilities is a significant social issue for the safety of teachers and students during the COVID-19 period. The CDC’s Science Brief (CDC and Science Brief, 2021) reported that children and adolescents could transmit contagious viruses to other people. The cumulative infection rates in children aged 0–4 years are approximately half that of children aged 5–17, which is almost equivalent to those in seniors aged 65 years or older. In a study conducted by Lopez et al. (2020), researchers verified that children in daycare centers are significant sources of virus transmission (Lopez et al., 2020; Chen
et al., 2020; Qiu et al., 2020), even though the conditions of the 12 infected children observed in three daycare facilities were mild or asymptomatic. In the contact tracing of 3 small to large child care facilities across the United States (CDC, 2021b) and in South Korea (MOHW, 2021a), the rate of symptomatic infections in children was lower than among adults (Walger et al., 2020), and deaths in infected children are rare (Walger et al., 2020).

In another study, Walger et al. (2020) pointed out that the outbreaks of SARS-CoV-2 in daycare centers and kindergartens may have only a limited impact on the further transmission of the SARS-CoV-2 virus due to low symptoms and severity. This is because the rate of symptomatic infections between children and adolescents is lower than among adults (Walger et al., 2020; CDC COVID-19 Response Team, 2020; Choi et al., 2020), and deaths in infected children are rare (Walger et al., 2020). Some researchers have indicated that the lower rates of virus infection in children might be due to lower exposure (e.g., school, daycare, and activity lockdown) and virus testing opportunities compared to adults (Reese et al., 2021).

In the statistics from Korea after the pandemic, the confirmed cases for ages 0–9 children were 12,543 (5.16%) of total cumulative confirmed cases (n = 243,317), and there were no deaths or severe cases (as of August 27, 2021) (MOHW, 2021d). Nevertheless, 36 cluster outbreaks have occurred since January 2021, with a total of 635 confirmed cases related to daycare centers and kindergartens (Table 2). Among all confirmed cases, indoor transmission in the daycare facilities was 45.5% (n = 289/635 cases), and the additional transmission out of the daycare facilities was 54.5% (n = 346/635 cases). The main transmission route was nursing teachers and students. They were infected in external facilities (e.g., homes, academies, churches, multi-use facilities). Then, infected teachers and students spread infectious particles to other teachers and students as virus containers in daycare centers and kindergartens. Newly infected teachers and students transmitted contagious viruses to their household members and acquaintances. In total in-house cases, the rate of daycare staff was 41.9% (n = 121/289 cases), and the rate of infected students was 58.1% (n = 168/289 cases) (KDCPA, 2021a). Therefore, in order to prevent the spread of SARS-CoV-2 in daycare centers, daycare centers should minimize the transfer from outside through reinforced virus measures, including regular body temperature checks and preemptive virus tests. Further, mitigation methods (e.g., natural ventilation, air purification, and sterilization) should be appropriately operated to remove infectious contaminants in the air and on the surfaces of objects to ensure a safe indoor environment in daycare centers.

### Table 1: Infection control measures for daycare centers and schools.

| Type | Control Measures | WHO (WHO Coronavirus disease (COVID-19): Schools, 2020; WHO, 2020b) | Korea (MOHW, 2021a) | United States (CDC, 2021; CDC, 2021b) | Germany (Ehrhardt et al., 2020) |
|------|------------------|---------------------------------------------------------------|-----------------------|--------------------------------------|--------------------------------|
| P    | Appointment of infection control manager/team               | Y                                                               | Y                     | N/A                                  |                                |
| P    | Education and guidance compliance for teachers and students | Y                                                               | Y                     | N/A                                  |                                |
| P    | Daily health screenings (e.g., body temperature)            | Y                                                               | Y                     | N/A                                  |                                |
| P    | Individual hygiene (e.g., hand hygiene, respiratory etiquette) | Y                                                               | Y                     | Y                                    | Y                              |
| P    | Facial mask in buildings                                    | Y                                                               | Only for teachers b   | N                                     |                                |
| P    | Facial mask outside buildings                                | N/A                                                             | Only for teachers b   | N                                     |                                |
| P    | Limit mixing between distinct groups                         | N/A                                                             | Y                     | N/A                                  |                                |
| P    | Limit any non-essential volunteers, visitors, and activities | N/A                                                             | Y                     | N/A                                  |                                |
| D    | Physical distancing between infants and toddlers             | N/A                                                             | Parent consent required | Y                                    |                                |
| D    | Reduced group sizes or activities                            | N/A                                                             | No cross-use of musical instruments | N/A                                  | Some                            |
| S    | Limited singing and use of instruments during extracurricular activities (e.g., music) | N/A                                                             | Y                     | N/A                                  |                                |
| S    | Cancelling/limited physical education                        | N/A                                                             | Y                     | N/A                                  |                                |
| S    | Cleaning/disinfection of high touch surfaces and air filters  | Y                                                               | Y                     | Y                                    | Y                              |
| S    | Cleaning/disinfection of transport vehicles                  | N/A                                                             | Y                     | N/A                                  |                                |
| S    | Cleaning/sanitizing drinking fountains                       | N/A                                                             | Y                     | N/A                                  |                                |
| S    | Exclusion of sick or suspicious children                     | Y                                                               | Y                     | Y                                    | Y                              |
| S    | Foodservice controls (e.g., social distancing, ventilated space, avoiding self-serve food, hand hygiene) | Y                                                               | Y                     | Y                                    | N/A                            |
| C    | Regular/interim ventilation of rooms                         | Y                                                               | Y                     | Y                                    | Y                              |
| C    | Flush-out before and after occupancy                         | Y                                                               | Y                     | N/A                                  |                                |
| C    | Exhaust fans in restrooms and kitchens                       | N/A                                                             | Y                     | N/A                                  |                                |
| C    | Considering high-efficiency particulate air (HEPA) filters or ultraviolet germicidal irradiation (UVGI) | N/A                                                             | Y                     | N/A                                  |                                |
| A    | Careful HVAC system operation (e.g., Disable recirculation, direct wind, and demand controls) | Y                                                               | Y                     | N/A                                  |                                |
| A    | Installation of physical barriers (e.g., reception desks and entryways) | N/A                                                             | Y                     | N/A                                  |                                |

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b Measure type: Prevention (P), Close and fomite source control (S), Airborne transmission control (A), Contaminant removal (C), and Density control (D).

b It is not compulsory for children to wear a mask. However, infants are recommended to wear a mask during group activities (e.g., singing and dancing, etc.) and when using vehicles.

* Infection control measures of the federal state of Baden-Württemberg in southwest Germany.
Facility overview

The case building of this study is a COVID-19 cluster outbreak facility in May 2021. The index case of the cluster outbreak was a teacher in a nursing room (NR)-2 (age 2) and an asymptomatic case. She was discovered through a preemptive examination by the facility on May 22, 2021. The first symptomatic person in the epidemiological investigation was a toddler (age 2) studying in NR3 (age 2), and the COVID-19 symptom appeared on May 16, 2021. The case of the first symptomatic person was confirmed on May 23 after 6 days through Polymerase Chain Reaction (PCR) test. Also, in the epidemiological investigation, 9 people (4 young children, 2 teachers, 3 family members) already had symptoms before the index case was reported, but they did not recognize it as COVID-19. As of June 18, 2021, a total of 28 cases were found in the R-daycare center, including 7 teachers, 13 students, and 7 teachers’ and students’ family members. Also, within the facility (family infection excluded), the attack rate of COVID-19 in the daycare center was 18.7% (n = 20/107). The primary case was not clearly identified in an epidemiologic investigation by the Korea Disease Control and Prevention Agency (KDCPA) (KDCPA, 2021b).

In terms of this daycare center, the KDCPA implemented the COVID-19 sampling of objects. A total of 7 out of 36 samples from the surfaces of objects (e.g., desk, mat, sleeping gear, doorknob) in nursery rooms and toilets were positive (19.4%, 7/36), and 6 out of 8 samples from the prefiltrers in air purifiers confirmed virus-positive (75.0%, 6/8). In particular, the viruses were detected on the prefiltrers of the air purifiers in nursing rooms, including NR2 (age 1), which had no patients (KDCPA, 2021b). This implies the potential for long-distance airborne virus transmission in the daycare center.

In the field survey, daycare teachers spent the most daytime with their children without transferring to adjacent classrooms. Teachers also ate meals in classrooms with infants and toddlers. Most nursing rooms had awning-type windows, but some spaces (e.g., playrooms, offices) had no windows for ventilation. The epidemiologic investigation (KDCPA, 2021b) surmised that fomite transmission (e.g., toy), contact transmission (e.g., singing, dancing, physical activity), and airborne virus transmission (e.g., could be the potential routes of this cluster infection. However, the transmission routes of the SARS-CoV-2 virus from the first symptomatic case (NR3; age 2) or index case (NR2; age 2) to distant classrooms remained unclear. Therefore, this study focused on the possibility of far-reaching indoor airborne contaminant transmission to prevent cluster outbreaks in daycare centers.

The R-daycare center was located on the podium floor (1st floor) of an apartment building in Sejong, Korea. It was a single-story daycare center consisting of 7 nursing rooms, an office, a counseling room, a playroom, a reference room, and a kitchen with a total building area of 243 m². The operating hours of the daycare center were 7:30 a.m. to 7:30 p.m. (12 h) on weekdays. A total of 106 occupants (79 infants and toddlers, 22 daycare teachers, and 5 external instructors) were registered in the daycare center for 13 classes (0–3 years old).

In terms of building systems, the heating and cooling systems were electric heat pump (EHP) systems mounted on the ceiling, and wall-mounted fans were also installed in nursing rooms as auxiliary cooling systems. Before the COVID-19 outbreak, cooling systems were not operated at the daycare center. The center was not equipped with mechanical ventilation systems, and thus natural ventilation through windows was the only way to introduce fresh outdoor air into nursing rooms during the pandemic. To supplement this, air purifiers were installed in each nursery room to improve indoor air quality. The air purifier in the nursing rooms was a 75 m²-type product with dual fans and three-stage air filtering, including 1) microfiber prefilter, 2) double deodorization filter, and 3) all-in-one composite filter (deodorization + fine particulate matter) and stand-alone air purifiers were installed in the hallway, nursing room #1, and playroom. The air filters were replaced by the manufacturer’s service every two months. Before the COVID-19 outbreak, the daycare center typically opened windows for natural ventilation and operated air purifiers during the daytime. The details of the facility and cluster outbreaks are provided in Table 3 and Fig. 1.

Experiment design and environmental conditions

This study tested the possibility of the long-distance spread of airborne viruses into adjacent classrooms in the R-daycare center. To this end, the researchers attempted to identify the potential transmission routes of airborne viruses on the air purifier prefilters that were found in samples. The air filtering performance of the virus-like particles was also investigated because air purifiers were the only available additional mitigation system, along with natural ventilation, in the daycare center.

The experiment was conducted from June 1st to 2nd, 2021. The indoor and outdoor environmental conditions during the experiment are shown in Fig. 2. According to the Korea Meteorological Administration
(KMA), the outdoor temperature on these days was 22.3–29.4 °C, and the external relative humidity was 36–92%. The external wind speed was 0.0–2.5 m/s (KMA, 2021). The measured indoor temperature (sensor 1, hallway) was 22.6–25.0 °C during the monitoring. The outdoor weather conditions during the experiments were similarly maintained compared to the pre-symptomatic period (May 13–15, Table 4).

In May, when COVID-19 occurred at the R-daycare center, the efficiency of natural ventilation seasonally decreased. The air temperature differences between indoors and outdoors were smaller than those in winter due to the air temperature rise in the spring season. Thus, in the case study building, outdoor air would not be sufficiently introduced in the spring, and the indoor airflow would be stagnant during the virus spread period.

Therefore, indoor airborne virus transmission between hallways and

Fig. 1. R-Daycare center plan and cluster infection cases.

Fig. 2. Indoor and outdoor environmental conditions during the experiment (June 1st-2nd, 2021).
adjacent classrooms was traced using virus-like particles in this study. Virus-like particles were sprayed in the potential virus sources (e.g., index case, first symptomatic patient, teacher’s meeting). In addition, the potential risk of no flush-out before and after space use was explored by monitoring unoccupied hours. This result shows the significance of flush-out for occupants the next day. For the experiment, an oil droplet generator, a smog generator, IAQ sensors, laser equipment, and various other sensors were utilized. A total of 10 air quality sensors were installed to detect virus-like particles in the nursing rooms and hallway. IAQ sensors can measure 0.3–10 μm particles with 98% counting efficiency (≥0.5 μm). Aerosol-sized particles were sprayed at 10 psi using a Laskin nozzle oil droplet generator (TSI Model 9307) that can release aerosol-sized oil particles with mean diameter of 1.0 μm and 30 l/min of the aerosol flow rate under normal operation (25 psi) in the air (TSI Incorporated, 2015). Laser visualization experiments were also performed to compare installation methods for air purifiers. The laser visualization observation showed the behavior of virus-like particles in the air using a smog generator, 10W and 5W diode-pumped solid-state (DPSS) laser was used to generate the laser sections with a fog generator (SAFEX, Model F2010). The laser sections visualize the real-time behavior of virus-like particles from an air contaminant source. Testo 405-V1 was used to record wind speed and air temperature in the outdoor environment. Testo 400 was installed in NR3 (age 2) to document indoor temperature and humidity. Fig. 3 shows the environmental conditions of this study.

4. Potential of long-distance transmission

In the case building, long-distance airborne propagation was conjectured as a virus route because several infected cases in different classrooms were far from the index case (age 43, teacher) and the first symptomatic toddler (age 2, student). Since there were no clear close contacts between daycare teachers and children in different classrooms during the open hours, identifying the potential for long-distance transmission could be helpful in understanding the COVID-19 outbreak routes in the daycare center. Therefore, in this section, several scenarios were tested to verify the potential risks of the spread of long-distance viruses.

4.1. Contaminant behavior under the current operations

The primary case of the R-daycare center outbreak was not identified in the epidemiological investigation by the KDCPA. Hence, this study tested suspicious virus sources, such as NR3 (age 2), where the first symptomatic patient (age 2) was found. According to the on-site interview, during the daycare hours, the classroom doors were closed, the windows were opened, and the air purifier and restroom fan were turned on in May 2021. After daytime classes (after 4 p.m.), the daycare center was regularly cleaned for about 30 min before the extended daycare classes began. During cleaning time, the windows and classroom doors were open, and the air purifiers and restroom fans were turned off.

Therefore, the experiment in this section included two parts of operating conditions in the R-daycare center (Table 5): regular class conditions and afternoon cleaning time conditions (Fig. 4 and Table 6).
In Fig. 4 (a), the virus spread from the infected location was tested in the classroom using an oil droplet generator. The virus-like particles were generated into NR3 (age 2) for 20 min to simulate airborne virus transmission under normal class operating conditions. In Figure 4 (b), 40 min of observation after Fig. 4 (a) shows how airborne virus-like particles can be spread in the R-daycare center during the afternoon cleaning time when the infected patient left the classroom. During the experiment, the indoor room temperature ($T_{db}$) of NR3 (age 2) was 22.7–24.5 °C, and the relative humidity (RH) was 58.3–64.4%. Outdoor weather was 24.0 °C and RH 62%, and wind speed and wind direction were 1.7 m/s and 140°, respectively (KMA, 2021).

Fig. 4 and Table 6 show the patterns of airborne transmission under the actual ventilation conditions in the R-daycare center. In Fig. 4(a), when virus-like substances were sprayed with the regular classroom conditions for 20 min, the virus-like substances were transferred from NR3 (age 2) to NR2 (age 2) through a shared restroom (IAQ#2). In the corridor (IAQ#3) adjacent to NR3 (age 2), the concentration of virus-like particles increased from 36 to 715 μg/m$^3$. This confirmed that virus-like particles could diffuse into the hallway due to air leakage through the door gaps. In terms of the possibility of long-distance transmission, the concentration of NR1 (age 1) (IAQ#7), 29.5 m away from the test site, increased by 33 μg/m$^3$ compared to before the experiment. In particular, after 19 min, the particle concentration increased from 14 to 29 μg/m$^3$ in NR1 (age 1) (IAQ#7), which indicates that virus-like particles can reach long distances through the air. However, the ratio of reaching virus-like substances is relatively low.

### Table 5

| Scenarios | Ventilation and Air Filtering Conditions |
|-----------|-----------------------------------------|
| Virus Location | Features | Windows | Air purifiers | Room doors | Restroom fans |
| NR3 (Age 2) | General operation in open hours (20 min jets) | All open | On (S) | All closed | On |
| Cleaning time (40 min) | All open | Off | All open |

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compared to air contaminant sources.

By contrast, 40 min of monitoring was conducted for airborne diffusion during cleaning time. The virus-like particle concentrations of NRs 2–3 (age two) and adjacent spaces were reduced due to natural ventilation and airborne transmission to the neighboring spaces. The concentrations of virus-like particles in the long-distance nursing rooms increased due to dispersion by indoor airflow movement, as shown in Fig. 4(b). This result indicates that virus-like particles could reach other adjacent spaces in a 40-min period under ventilation conditions during cleaning time. During the cleaning time, the reduction rate of virus-like particles was 76.5% in NR3 (age 2). Since the existing literature recommends at least 95% virus removal through outdoor air for safety (ASHRAE Epidemic Task Force, 2020), the current removal performance was not sufficient to lower airborne virus concentration and control airborne virus transfer between indoor spaces. Above all, all multi-rooms in the daycare center were connected by the central corridor, which limited natural ventilation performance during the daytime. Therefore, to sufficiently mitigate airborne contaminants, the daycare center should extend the ventilation hours in the cleaning time or install mechanical systems to increase the outdoor air ventilation rates in nursing rooms.

### 4.2. Airborne transmission from potential virus sources

In airborne virus transmission, the location of the infected people can significantly impact the results of experiments. In the outbreak of the R-daycare center, there were several potential virus sources, such as nursing room (NR)-2 (age 2), NR3 (age 2), and NR (age 3). Among these, NR3 (age 2) was tested in Section 4.1. Thus, in this section, NR2 (age 2), where the index case stayed, and NR (age 3), where daycare teachers had a meeting (May 17th), were tested as potential virus sources. To trace the possible spread of contagious viruses, this study conducted an experiment with ventilated conditions (Table 7) since, typically, classrooms operated natural ventilation and air purifiers before the outbreak. For these experiments, virus-like particles were sprayed at 20 psi for 20 min using an oil droplet generator. In NR2 (age 2), the indoor air temperature (\(T_{a2}\)) was 24.0–24.9 °C, and the relative humidity was 51.3–57.3%. In NR (age 3), the room temperature was 24.4–25.0 °C, and the relative humidity was 50.2–52.8% during the monitoring. External air conditions in the experiment of NR2 (age 2) were 25.9 °C and RH 44% with a wind speed of 1.1 m/s and a wind direction of 290°, and outdoor conditions in NR (age 3) were 26.5 °C and RH 42% with a wind speed of 0.9 m/s and a prevailing wind direction of 20° (KMA, 2021).

Table 8 and Fig. 5 summarize the results of this section.

In Fig. 5(a), the experiment of airborne virus spread in NR2 (age 2) (IAQ#5) represents when an infected person exhales the infectious viruses indoors. In the results, the virus-like substances reached all the nursing rooms within 20 min through indoor airflow, although the concentrations of virus-like substances varied. The highest concentrations were found in the shared restroom (IAQ#2), NR2 (age 2), and hallways (IAQ#3), neighboring with NR3 (age 2) (IAQ#1). These indicate that when the index case occupied NR2 (age 2), the airborne transmission was likely to occur between neighboring nursing rooms. Within 12–13 min after the virus-like particle ejection, increments in particle concentrations were observed in NR1 (age 1) (IAQ#7) and NR (age 0) (IAQ#8). Compared with the concentration of NR2 (age 2), the reaching rates in NR1 (age 1) (IAQ#7) and NR (age 0) (IAQ#8) at the peak time were 14.2% (198/1392 μg/m³) and 11.6% (161/1392 μg/m³), respectively. However, the virus-like particles took approximately 19 min to reach NR2 (age 1), so the speed of airborne diffusion was relatively slow.

During the outbreak period, the only chance that daycare teachers could have close contact was the teachers’ meeting in NR (age 3) (IAQ#9). In the observation of Fig. 5(b), when virus-like particles were diffused in NR (age 3), particles could spread out more easily than in Fig. 5(a) due to natural ventilation from outside. The spread time to reach NR2 (age 2) and NR3 (age 2), which are the most distant spaces from NR (age 3) (IAQ#9), was about 6 min. This indicates that long-distance transmission from NR (age 3) was much faster compared to the experiment of NR2 (age 2) (IAQ#5) in Fig. 5(a). In addition, the reaching rates at the peak time were 16.1% (237/1469 μg/m³) and 17.2% (262/1522 μg/m³) for NR2 (age 2) (IAQ#5) and NR3 (age 3) (IAQ#1), respectively, which was higher than that of the virus-like particle transmission of NR2 (age 2) (IAQ#5). Therefore, the potential for long-distance transmission should not be overlooked, even when providing natural ventilation and operating air purifiers during the open hours in the daycare center.

### 4.3. Contaminant accumulation during unoccupied hours

During the COVID-19 period, health authorities and professional societies recommended flush-out before and after space occupancy. Similarly, the Ministry of Health and Welfare (MOHW) (MOHW, 2021b) encourages natural ventilation before and after occupancy in daycare centers, but there is no specific guidance for flush-out operations (e.g., required ventilation volume, operating methods). Thus, the impact of natural ventilation before and after occupancy in daycare centers is not clear. In general, daycare centers in Korea have 12 h of unoccupied time,
### Table 8
Airborne contaminant transmission and reduction in adjacent nursing rooms.

| Cases                  | Value                      | Airborne Contaminant Sensors (μg/m³) |
|------------------------|----------------------------|--------------------------------------|
|                        | IAQ#1 | IAQ#2 | IAQ#3 | IAQ#4 | IAQ#5 | IAQ#6 | IAQ#7 | IAQ#8 | IAQ#9 | IAQ#10 |
| NR2 (Age2):IAQ#5       |        |       |       |       |       |       |       |       |       |        |
| Initial value          | 63.0   | 159.0 | 104.0 | 97.0  | 125.0 | 43.0  | 60.0  | 39.0  | 15.0  | 11.0   |
| Peak value             | 784.0  | 1529.1| 1060.6| 414.0 | 1705.6| 97.0  | 198.0 | 161.0 | 25.0  | 41.0   |
| After 20 min           | 765.0  | 1433.8| 850.0 | 414.0 | 1587.4| 44.0  | 165.0 | 131.0 | 20.0  | 41.0   |
| Change<sup>a</sup>     | 702.0  | 1274.8| 746.0 | 317.0 | 1462.4| 1.0   | 105.0 | 92.0  | 5.0   | 30.0   |
| Ratio (%)<sup>a</sup>  | 1214%  | 902%  | 817%  | 427%  | 1267% | 102%  | 275%  | 336%  | 133%  | 373%   |
| NR (Age3):IAQ#9        |        |       |       |       |       |       |       |       |       |        |
| Initial value          | 16.0   | 22.0  | 23.0  | 29.0  | 13.0  | 23.0  | 16.0  | 24.0  | 40.0  | 21.0   |
| Peak value             | 262.0  | 297.0 | 488.0 | 1283.8| 237.0 | 1006.8| 998.8 | 1225.6| 1615.6| 69.0   |
| After 20 min           | 230.0  | 246.0 | 385.0 | 1160.3| 189.0 | 906.2 | 900.0 | 985.6 | 1432.1| 26.0   |
| Change<sup>a</sup>     | 214.0  | 224.0 | 362.0 | 1131.3| 176.0 | 883.2 | 884.0 | 961.6 | 1392.1| 5.0    |
| Ratio (%)<sup>a</sup>  | 1438%  | 1118% | 1674% | 4001% | 1454% | 3940% | 5625% | 4107% | 3580% | 124%   |

<sup>a</sup> Change values and change ratios refer to the differences of virus similar particles between initial values and after 20 min values.

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**Fig. 5.** Airborne contaminant transmission to adjacent nursing rooms.
from 7:30 p.m. to 7:30 a.m. before open hours. If air contaminants are not fully removed after use, they may remain in the indoor air until the next morning. In the field study, the R-daycare center performed natural ventilation before class hours and during cleaning time. However, whether the virus transmission at an unoccupied time was prevented was not identified in the epidemiological investigation of the entire daycare center.

Therefore, this experiment monitored how virus-like particles could be transmitted to neighboring rooms during the unoccupied time when an infected patient exhaled infectious viruses during the daytime, and no flush-out was conducted after space use. Table 9 shows the unoccupied time conditions when the daycare center closed. The test was carried out in NR (age 3) (IAQ#9), and the particles were ejected at 20 psi for 15 min. The concentration change of airborne particles in the daycare center was observed for 15 h from the evening to the next morning. At this time, the indoor environmental conditions in NR (age 3) were 23.3–25.0 °C of air temperature and 50.3–58.6% of relative humidity. Outside air conditions were 17.4–25.9 °C of indoor air and RH 43–79%. Wind speed and direction in the outdoor environment were 0.0–1.6 m/s and 70–320°, respectively (KMA, 2021).

In the results, the monitoring in Fig. 6 and Table 10 showed that the concentrations of virus-like particles were leveled in most nursing rooms after about 6 h, and thereafter, the changes in particle concentrations were not significant until the next morning. In particular, in NR2 (age 2) (IAQ#5) and NR3 (age 2) (IAQ#1), which are distant from the virus source (NR (age 3)), the extent of changes was not notable during the over 12 h. In NR2 (age 2) (IAQ#5) and NR3 (age 2) (IAQ#1), the concentration of virus-like particles peaked after 3 h from the ejection start, and then the density of particles decreased only up to 30%–30.5% after 9 h. In overnight monitoring, NR (age 3) (IAQ#9) showed 65.8% of the reduction rate compared to the peak concentration during 12 h. However, the total concentration reduction of virus-like particles (Fig. 6(b)) from all measured indoor spaces was only 38% during 12 h and 44% during 14 h after the peak value through air leakage. The decrease in the total concentration of the daycare center implies that the virus-like particles sprayed from NR (age 3) (IAQ#9) were diffused to other adjacent spaces during unoccupied nighttime. This result also indicates that the airborne virus can be trapped in nursing rooms during the unoccupied time. Thus, if effective measures are not applied in the nursing rooms before and after occupancy, particles would be transferred to the other rooms over long distances during nighttime. This means that teachers and students in the daycare centers can be exposed to infectious diseases the next day through nighttime long-distance transmission without direct contact with the infected person. Therefore, sufficient ventilation before and after space use can be helpful in preventing residual airborne contaminants transfer before reopening the facility the following day.

5. Mitigation performance of the R-daycare center

In the R-daycare center, the cluster infection of SARS-CoV-2 occurred in May 2021. Before the outbreak, this facility complied with the government’s quarantine guidelines, such as frequent natural ventilation, everyday body temperature checks, wearing masks, and restrictions on visits from outsiders. Further, the R-daycare center opened windows and operated the air purifiers in auto mode during class time. Despite such efforts, cluster infections occurred in the daycare center. Therefore, this section evaluated the removal trends of virus-like particles in nursing rooms and investigated the impact of air purifiers on airborne transmission as an alternative measure for virus mitigation in daycare centers.

5.1. Contaminant removal trends

The R-daycare center had continuously ventilated the classrooms through windows and filtered indoor air using wall-mounted and stand-alone air purifiers to improve air quality during open hours. However, the performance of mitigation strategies can vary depending on the indoor and outdoor environment. Therefore, to verify this, this section monitored the concentrations of virus-like particles from NR (age 3) (IAQ#9) and NR2 (age 2) (IAQ#5) for 40 min after 20 min of virus-like particles sprayed in Section 4.2. During the experiment, windows, and doors were opened, and the air purifiers operated in strong mode. Fig. 7 and Table 11 show the virus removal trends in NR (age 3) (IAQ#9) and NR2 (age 2) (IAQ#5). Since environmental differences affect the airborne transmission of virus-like particles depending on the location of the virus ejection source (e.g., NR, age 3 (IAQ#9) and NR2, (age 2) (IAQ#5)), mitigation impacts of natural ventilation and air purifiers can be differentiated in nursing rooms. For example, in Fig. 7(a), the concentrations of virus-like substances in NR (age 2) (IAQ#5) were reduced within 20 min in most spaces. However, since NR-age 3 (IAQ#9) represented a faster indoor diffusion rate than NR-age 2 (IAQ#5), several spaces could not be completely mitigated within 40 min. Therefore, in order to prevent cluster infection through airborne contaminant transmission in daycare centers, it is important to develop customized plans for the facilities, including ventilation hours or rates based on the actual spread and removal rates in indoor spaces. For this, additional mechanical ventilation devices or new ventilation windows should be considered for the daycare center.

5.2. Air purifiers for airborne virus controls

5.2.1. Impact of operating modes

In this study, the potential risk of long-distance transmission of an airborne virus was tested in the R-daycare center, where the COVID-19 cluster infection occurred in May 2021. Long-distance transmission from potential virus sources was simulated using aerosol-sized particles and sensor monitoring in nursing rooms. Typically, spring in Korea is dry and warm, and thus, the efficiency of natural ventilation is lowered due to the reduced air temperature differences between indoors and outdoors. Therefore, natural ventilation may not be sufficient in facilities without mechanical ventilation systems or air filtering devices. Previous studies have verified the effectiveness of high-performance air filters in alleviating the potential transmission of SARS-CoV-2 (Agarwal et al., 2021; Mousavi et al., 2020; Zhao et al., 2020; Kapilan and Rao, 2021). However, the impact of the air purifier on virus removal performance is affected by the operating modes. Therefore, an experiment was conducted to evaluate the filtering performance in NR3 (age 2) (IAQ#1), where the first symptomatic patient was found. The concentration fluctuations of the virus-like particles were measured according to the operating modes (e.g., strong, weak, off) using a wall-mounted air purifier. The windows and doors were closed during the experiment to exclude the influence of natural ventilation. The virus-like particles were sprayed at 20 psi for 20 min using the oil droplet generator, and then the particle removal performance was measured for 40 min. Indoor environmental conditions during the monitoring were 23.3–25.5 °C of room temperature and 48.8–56.7% of relative humidity. Table 12 shows the case scenarios for the air purifier used in this study.

Fig. 8 and Table 13 show the time-series transfer and summary of the virus-like substances when the air purifier was operated in three different modes in NR3 (age 2): 1) off, 2) strong (S) mode, and 3) weak (W) mode. In the weak (W) mode, the concentration of virus-like particles was reduced by about 27% after 1 h compared to the condition.
with no air purifier. In the strong (S) mode, the wall-mounted air purifier confirmed an approximately 86% reduction in aerosol-sized particles. This evidence of operating modes verified that air purifiers were effective for infectious virus controls compared to the 5.8% reduction with the no air purifier. Although the impact of air purifiers can vary depending on installation methods and capacity, air purifiers can be regarded as an alternative to alleviate the spread of infectious substances and supplement insufficient outdoor air fractions during opening hours at the R-daycare center.

5.2.2. Impact of installation methods

After the pandemic, scientific societies discussed the usefulness of air purifiers due to the possibility of long-distance transmission due to direct wind from the grills. The risk of direct wind from HVAC systems has been identified and discussed in several studies (Yu et al., 2021; Lu et al., 2020) and guidance (ECDC, 2020; KDCA, 2020; Kwon et al., 2020). Therefore, in this section, the impact of installation methods on transmission behavior was verified using the laser visualization experiment using a stand-alone air purifier. In the R-daycare center, two types of air purifiers were used, such as a wall-mounted type in most nursing

### Table 10
Airborne Contaminant Concentration without Flush-Out after Use (unit: μg/m³).

| Airborne Contaminant Sensors | IAQ#1 | IAQ#2 | IAQ#3 | IAQ#4 | IAQ#5 | IAQ#6 | IAQ#7 | IAQ#8 | IAQ#9 | IAQ#10 |
|-----------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------|
| Initial value               | 36    | 63    | 160   | 89    | 46    | 92    | 77    | 50    | 23    | 30     |
| Peak value                  | 748.0 | 933.5 | 900.0 | 2035.6| 839.0 | 1396.8| 1170.9| 1783.2| 1976.5| 802.0  |
| After 12 h                  | 520.0 | 636.0 | 603.0 | 729.0 | 592.0 | 643.0 | 552.0 | 669.0 | 676.0 | 575.0  |
| Reduction                   | -228.0| -297.5| -297.0| -1306.6| -247.0| -753.8| -618.9| -1114.2| -1300.5| -227.0 |
| Ratio (%)                   | -30.5%| -31.9%| -33.0%| -64.2%| -29.4%| -54.0%| -52.9%| -62.5%| -65.8%| -28.3% |
Table 11
Airborne contaminant reduction in nursing rooms.

| Cases          | Value          | Airborne Contaminant Sensors (μg/m³) |
|----------------|----------------|--------------------------------------|
|                | IAQ#1          | IAQ#2      | IAQ#3      | IAQ#4      | IAQ#5      | IAQ#6      | IAQ#7      | IAQ#8      | IAQ#9      | IAQ#10     |
| NR2 (Age2):IAQ#5 | Initial value  | 765.0      | 1433.8     | 850.0      | 414.0      | 1587.4     | 44.0       | 165.0      | 131.0      | 20.0       | 41.0       |
|                | Peak value     | 834.0      | 1575.0     | 876.0      | 414.0      | 1587.4     | 97.0       | 229.0      | 170.0      | 48.0       | 76.0       |
|                | After 40 min   | 30.0       | 35.0       | 33.0       | 37.0       | 21.0       | 28.0       | 32.0       | 27.0       | 21.0       | 16.0       |
|                | Change¹        | –735.0     | –1398.8    | –817.0     | –377.0     | –1566.4    | –16.0      | –133.0     | –104.0     | 1.0        | –25.0      |
|                | Ratio (%)      | 3.9%       | 2.4%       | 3.9%       | 8.9%       | 1.3%       | 63.6%      | 19.4%      | 20.6%      | 105.0%     | 39.0%      |
| NR (Age3):IAQ#9 | Initial value  | 230.0      | 246.0      | 385.0      | 1160.3     | 189.0      | 906.2      | 900.0      | 985.6      | 1432.1     | 26.0       |
|                | Peak value     | 393.0      | 364.0      | 763.0      | 1472.6     | 445.0      | 1006.8     | 994.4      | 1289.1     | 1434.7     | 135.0      |
|                | After 40 min   | 68.0       | 90.0       | 250.0      | 107.0      | 87.0       | 109.0      | 93.0       | 108.0      | 28.0       | 25.0       |
|                | Change¹        | –162.0     | –156.0     | –135.0     | –1053.3    | –102.0     | –797.2     | –807.0     | –877.6     | –1404.1    | –1.0       |
|                | Ratio (%)      | 29.6%      | 36.6%      | 64.9%      | 9.2%       | 46.0%      | 12.0%      | 10.3%      | 11.0%      | 2.0%       | 96.2%      |

¹ Change values and change ratios refer to the differences of virus similar particles between initial values and after 40 min values.
rooms and stand-alone types installed in the hallway, nursing room #1, and playroom. Since the wall-mounted air purifiers were already installed above the height of the child and their wind direction avoid occupants, the stand-alone air purifier was selected and tested for improvements on installation and operations.

Fig. 9 shows the visualized diffusion characteristics of virus-like particles between a stand-alone air purifier and air contaminant sources. Fig. 9 (a) shows the behavior of virus-like particles when the virus source was located in the lower front of the air purifier. In this case, most of the virus-like particles were out of the exhaust path for purified air from the outlet grill. Therefore, most airborne contaminants were sucked into inlet pores for filtering, and then the purified air was discharged into the indoor air. However, the result in Fig. 9 (b) shows the potential risk of virus transmission boosted by the air purifier. When virus-like particles were scattered in the exhaust path of the diffuser grill, direct airflow from the grill pushed the airborne contaminants into the indoor space without filtration. Therefore, to reduce the potential risk of installation and operation methods in air purifiers during the pandemic, the air purifier should be installed higher than the height at which people breathe, or its outlet direction could be set to avoid occupants. These implications can help ensure the effectiveness of the air purifier with virus safety in closed spaces.

6. Discussion

In this study, we explored experimental evidence of airborne virus transmission from a COVID-19 cluster infection in the R-daycare center in Sejong, Korea. To achieve the research goals, virus-like particles were used as potential virus infection sources. The concentration of the virus-like particles was traced in real-time to monitor airborne transmission and contaminant removal rates by natural ventilation and air purifiers in the experiments. In addition, the removal performance of the air purifiers was confirmed using particle concentration and laser visualization observation, depending on the ventilation and air purifier operation modes. Even though the R-daycare center fully complied with governmental quarantine actions of health authorities before the outbreak (e.g., fever checks, disinfection, personal protection equipment, and limited visits of external visitors), the COVID-19 outbreak could not be prevented in the daycare center. This fact implies that further research and effort are thoroughly required to improve virus safety in multi-use facilities, such as daycare centers. For example, the risk from indoor and outdoor air contaminants should also not be overlooked to ensure the occupant’s health, which can influence the airborne virus transmission and severity/mortality of infectees. Therefore, this study investigated the potential of far-reaching air transmission based on the fact of surface sampling in the epidemiological investigation in the

| Table 12 |
| --- |
| **Experiment scenarios for air purifiers.** |

| Scenarios | Ventilation and Air Filtering Conditions |
| Source Location | Features | Windows | Air Purifiers | Room Doors | Restroom Fans |
| NR3 (Age2): IAQ#1 | No air purifier | All closed | Off | All closed | Off |
| Air purifier (strongest mode) | Air purifier | All closed | On (S) | All closed | Off |
| Air purifier (weakest mode) | All closed | On (W) | All closed | Off |

| Table 13 |
| --- |
| **Summary of air purifier modes on airborne contaminant controls.** |

| Operating Modes | No Air Purifier | Air Purifier (S) | Air Purifier (W) |
| --- | --- | --- | --- |
| Initial concentration (μg/m³) | 16.0 | 23.0 | 29.0 |
| Peak value (μg/m³) | 1508.8 | 1500.9 | 1543.2 |
| Mean (μg/m³) | 1438.4 | 773.8 | 1373.5 |
| After 1 h (μg/m³) | 1420.6 | 205.0 | 1036.8 |
| Reduction (%) | 5.8% | 86.3% | 32.8% |

| Reduction (%) versus no air purifier mode | N/A | 85.6% | 27.0% |

![Fig. 8. Impact of the air purifier on airborne contaminant mitigation.](image-url)
daycare center. The key findings are summarized as follows.

1) In the transmission from the nursing room (NR3 age 2) where the first symptomatic patient was found, the virus-like particles spread over a long distance to the adjacent spaces through the indoor airflow. In the R-daycare center, outdoor air ventilation was limited due to small opening areas in the awing-type windows and no mechanical ventilation systems. The current indoor environment might influence the extended floating time of the virus-like particles in the air and the prolonged exposure of occupants in the nursing rooms.

2) To evaluate the unoccupied hours (e.g., cleaning time (about 30 min after 4 p.m.), unoccupied time at night (7:30 p.m.–7:30 a.m.)), the concentrations of the virus-like particles were monitored during the night after spraying aerosol-sized contaminants at 5 p.m. on June 1st to the next morning June 2nd in the closed space. After 15 h, the researchers found that 34.2–71.7% of these airborne virus-like particles remained in the rooms compared to the peak time concentrations. The next morning, concentrations of virus-like substances were equalized in most spaces without complete removal. This indicates that when airborne contaminants are not sufficiently eliminated after use or before reopening at daycare centers, airborne viruses can be delivered over long distances to virus-free spaces during the night. Since the SARS-CoV-2 virus can survive in aerosols for hours and up to days on surfaces, depending on the environmental conditions (ECDC, 2020; KDCPA, 2020), the possibility of airborne transmission at unoccupied hours should be carefully considered for safety. This result, therefore, recommends sufficient flush-out before and after occupancy to take precautions against possible long-distance exposure of the SARS-CoV-2 virus in daycare centers.

3) In the experiment on air purifier fan modes, the concentration of virus-like particles decreased by about 27% and 86% in the weak (W) and strong (S) modes, respectively, compared to the condition with no air purifier. Even though there is a potential risk of delivering virus-like particles by direct airflow from the air purifier outlet, given the extended stay of teachers and children in the closed space, air purifiers with high-performance filters should be considered as an additional measure.

4) The climate of the external environment can affect the indoor diffusion characteristics of virus-like particles in daycare centers. In spring, natural ventilation through windows in daycare centers is lowered due to the reduced air temperature difference between indoors and outdoors, and the outside wind speed is also lower than in winter. In the results of the R-daycare center, complementary measures (e.g., longer ventilation hours, additional ventilation windows, or mechanical ventilation) are recommended to ensure better safety from airborne viruses, regardless of seasonal changes.

5) In the experiments, the transmission paths of airborne viruses were mainly affected by source location (e.g., nursing room), usage behavior (e.g., door and window open/closed), and architectural layouts (e.g., interior partitions and walls). The source locations (e.g., Nursing room-2 (Age 2), Nursing room-3 (Age 2), Nursing room (Age 3)) influenced the transmission direction, time, and concentrations. Hallways were primary paths to transport virus-like particles between nursing rooms. Lastly, restrooms between nursing rooms are vulnerable if an infected person emits virus-containing aerosols into the space while using the restroom. If restroom doors were not closed during the
During the last two years, infectious viruses and variants (e.g., Delta and Omicron) have been a critical threat to everyday life and health. The threats of invisible viruses and evolved infectivity require people to be prepared for every situation in buildings. In addition, although the virus transmission routes in buildings have been identified in many parts, the outbreak location and the scale of infection vary due to different building environments. This study analyzed the possibility of airborne virus transmission based on the evidence of viruses found in the air purifier filter samples in a cluster outbreak case of the R-daycare center and identified mitigation performance of the daycare center. Several experimental scenarios were conducted to understand the behavior of airborne virus-like particles and diagnose the effectiveness of the current mitigation measures. The experiments verified that the results of airborne virus transmission can be used to describe the long-distance transfer in the actual outbreak. Therefore, the findings of this study should be considered to improve the readiness of daycare centers during the pandemic, especially in Korea, because many daycare centers are exposed to similar building environments like R-daycare center.

Last but not least, to the best of our knowledge, this study is one of the few studies that has investigated long-distance transmission based on the actual outbreak in the daycare center. However, the characteristics of the SARS-CoV-2 virus have yet to be perfectly identified and fully described. The behavior and actual infectivity of the SARS-CoV-2 virus would very vary depending on indoor and outdoor environments (e.g., virus source location, discharge rates, patient behavior, and indoor and outdoor climatic conditions). Therefore, further studies are necessary to confirm the possibility of airborne SARS-CoV-2 virus transmission through several case studies.

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### 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.

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