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# Verification of Ventilation and Aerosol Diffusion Characteristics on COVID-19 Transmission through the Air Occurred at an Ice Arena in Japan

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**Abstract:** This study is about a COVID-19 outbreak and ventilation measures taken against COVID-19 transmission through the air occurred at an ice arena in Japan. The ice arena has been known to have a deterioration of indoor air quality affected by CO, $NO_2$ and so on, and a total of 172 persons were infected with SARS-CoV-2, including the players and the spectators related to an ice hockey game in 2022. Given the suspected transmission through the air as one of infection routes, the primary objective of this study was to investigate the COVID-19 outbreak to verify the ventilation characteristics and aerosol diffusion characteristics. Additionally, the possibility of COVID-19 transmission through the air and the potentially effective ventilation measures in an ice arena are discussed. It was determined that the virus-containing aerosol was released from a player in the ice rink and accumulated in the cold air spot. After that, it was highly possible that it diffused from the player benches to the spectator seats due to the players' movements under this unique air-conditioning and ventilation system. Judging from the results of genomic analysis, ventilation characteristics, and aerosol diffusion characteristics, the possibility of COVID-19 transmission through the air cannot be ruled out in an ice arena. The results of ventilation measures implemented in response to this problem confirmed that the integration of a lower-level exhaust fan based on cold air characteristics into the existing ventilation system is a relatively straightforward solution with the potential to be highly effective. While there is an option to refrain from using the ice arena in the event of an increased risk of mass infection during a pandemic, the findings of this study will contribute to an option to facilitate the smooth operation of ice arenas while implementing ventilation measures.

**Keywords:** ice arena; COVID-19; transmission through the air; ventilation; aerosol diffusion; ice hockey

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**Citation:** Kikuta, K.; Omori, S.; Takagaki, M.; Ishii, Y.; Okubo, K.; Ohno, Y.; Fujiya, Y.; Kurosu, H.; Shimada, T.; Sunagawa, T.; et al. Verification of Ventilation and Aerosol Diffusion Characteristics on COVID-19 Transmission through the Air Occurred at an Ice Arena in Japan. *Buildings* **2024**, *14*, 1632. https://doi.org/10.3390/buildings14061632

Academic Editor: Theodore Stathopoulos

Received: 22 April 2024
Revised: 20 May 2024
Accepted: 31 May 2024
Published: 2 June 2024

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## 1. Introduction

An ice arena is categorized as a specific building for the special use of various entertainments. In previous reports on the air environment in ice arenas, measures against air pollution from the exhaust gas of ice-making trucks were investigated [1,2]. Lee et al. measured high concentrations of CO and $NO_2$ in an indoor ice skating rink and evaluated methods for reducing air pollutants, emphasizing the importance of ventilation and reduced resurfacer operations for maintaining clean air quality [3]. Yoon et al. monitored

$NO_2$ levels in ice skating rinks in the greater Boston area, identifying ventilation as a key factor in mitigating indoor pollution from ice resurfacing equipment [4]. Pennanen et al. investigated indoor $NO_2$ concentrations in Finnish ice arenas, highlighting the influence of the ice resurfacer power source and arena volume on pollutant levels and recommending abatement measures [5]. Guo et al. monitored indoor air quality in Hong Kong ice rinks, finding elevated levels of pollutants attributed to ice resurfacers with combustion engines, indicating potential health risks for occupants [6]. Salonen et al. analyzed health risks associated with poor indoor air quality in Finnish ice arenas, identifying emission sources and advocating for regulatory measures to ensure safe sports environments [7]. Related to that, Drake et al. reported a case of respiratory illness linked to toxic indoor air pollutants in an ice arena, emphasizing the importance of identifying and addressing environmental hazards in recreational facilities [8].

In addition to CO and $NO_2$, Bragoszewska et al. assessed indoor air quality in an ice rink, finding higher bacterial concentrations when the ventilation system was off and highlighting the importance of ventilation for maintaining a healthy indoor environment [9]. Du et al. investigated indoor PM2.5 concentration in a renovated ice sports venue, finding a strong correlation with outdoor PM2.5 and recommending specific temperature and humidity controls for audience comfort and air quality improvement [10].

On the other hand, ice stability and the prevention of fog are primary objectives of the air-conditioning and ventilation system and their maintenance in an ice rink. There is a concern that dense cold air stays above the ice rink and causes poor ventilation in ice arenas. Regarding studies on energy saving and ventilation system, Piché et al. compared different ventilation systems in Canadian ice rinks, demonstrating energy and cost savings achieved by using warm air from refrigeration systems for ventilation or employing heat exchangers [11]. Li et al. proposed a zoning air-conditioning scheme for ice arenas, with different ventilation systems for the ice area and spectator stands, aiming to maintain sports standards near the ice while providing a comfortable environment for spectators [12]. Lin et al. conducted on-site measurements in ice arenas to study the impact of air distribution systems on temperature and humidity, finding significant variations and proposing statistical models for precise environmental control [13].

The COVID-19 pandemic occurred in a situation where both energy saving and good air quality are required. According to COVID-19-related studies, Krug et al. evaluated the effectiveness of return-to-play protocols in preventing SARS-CoV-2 transmission in youth ice hockey, implementing stringent measures resulting in no within-program COVID-19 transmission despite high community incidence [14]. However, outbreaks of infection at ice hockey games have been occurring worldwide. Kuitunen et al. reported on a COVID-19 outbreak in an amateur ice hockey team, highlighting the potential for asymptomatic carriers to spread the virus and advocating for protocols to prevent team-to-team transmission [15]. In the U.S., an outbreak of infection at an ice hockey game was reported [16].

Furthermore, a large outbreak of infection occurred in an ice hockey game held in Kushiro Ice Arena in January 2022. The outbreak of infection was investigated, and it was found that the COVID-19 outbreak could have occurred between players or team members and spectators who were at a long distance. This large case involving spectators is very different from other cases and should be investigated from epidemiological and engineering approaches. Given the suspected transmission through the air as one of infection routes, it is crucial to implement ventilation measures that align with the unique characteristics of ice arenas. Regarding airborne transmission, as the COVID-19 pandemic persists, major health authorities such as the World Health Organization (WHO) and the US Centers for Disease Control and Prevention have acknowledged the significance of airborne transmission of SARS-CoV-2 in 2020 [17], and the importance of short-range airborne transmission in 2021 [18]. In a recent development, the report [19] defines the phrase 'transmission through the air' and emphasizes the importance of ensuring adequate ventilation as one of the public health measures. Although the building types and spatial scales differ from an ice arena, the effectiveness of ventilation measures against COVID-19 has been documented

in various research papers [20–23]. Therefore, the primary objective of this study was to investigate this particular COVID-19 outbreak, to verify the ventilation characteristics and aerosol diffusion characteristics, and to discuss the possibility of COVID-19 transmission through the air and the potentially effective ventilation measures in an ice arena.

## 2. Materials and Methods

### *2.1. COVID-19 Outbreak Overview*

On 15 and 16 January 2022, Asia League Ice Hockey Games (the Games, abbreviated here) were held and the members of two teams (Team A and Team B), the officials in the Games, and the spectators were infected. As shown in Figure 1 and Table 1, players and staff members of teams were the first to develop COVID-19, followed by SARS-CoV-2 transmission among officials and spectators. Out of the 172 infected persons, 102 were spectators (59% of all infected persons), and all 42 players were infected (100% positivity rate). The virus was classified as the Omicron variant (BA.1.1.2) by genomic analysis. As shown in Figure 2, positivity rates among spectators varied depending on the location of the seats on both 15 and 16 January 2022. The rate was from 0% (I) to 29% (A, B) and the number of infected persons was particularly high on the west side near the player benches.

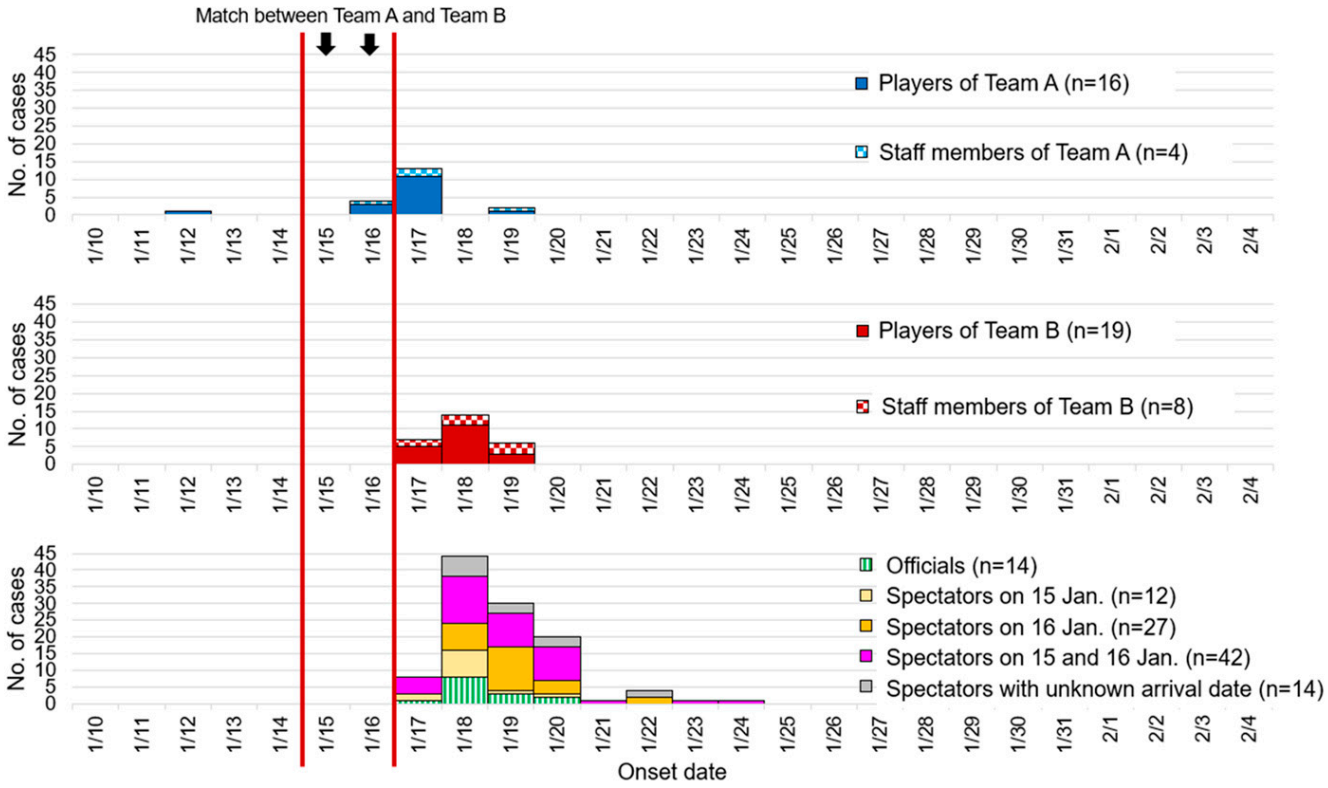



**Figure 1.** Epidemic curve of SARS-CoV-2 transmission.

**Table 1.** Positivity rates of SARS-CoV-2 transmission.

| | Percentage of All Infected Persons | Positivity Rates (Positives/Samples) |
|---|---|---|
| Players | 24% (42/172) | 100% (42/42) |
| Staff members | 8% (13/172) | 76% (13/17) |
| Officials (inside of the ice rink) | 3% (5/172) | 36% (5/14) |
| Officials (outside of the ice rink) | 6% (10/172) | 16% (10/62) |
| Spectators | 59% (102/172) | 12% (102/867) |

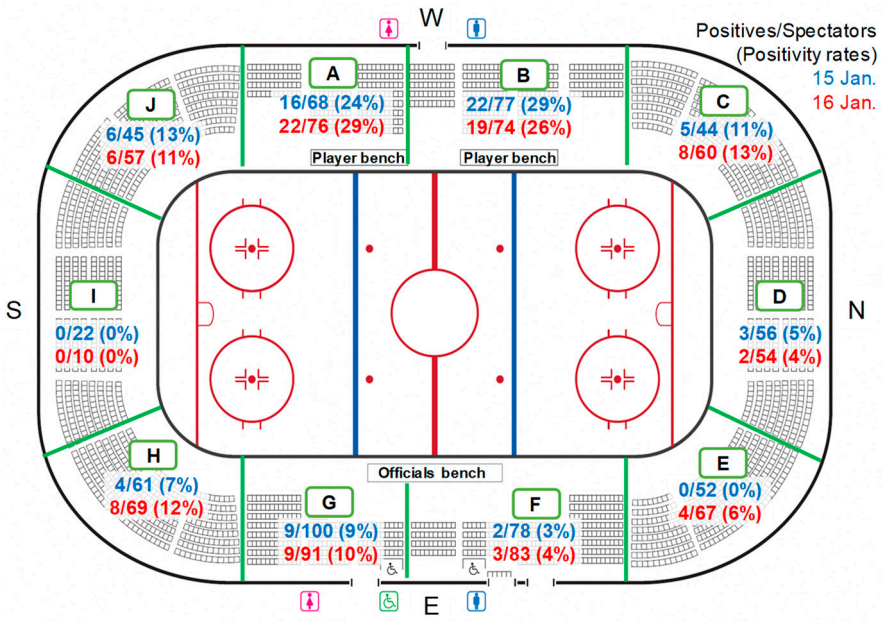



**Figure 2.** Positivity rates by location among spectators.

On the ice rink, the physical contact between players and the closeness of players and referees was seen, but it is natural to think that there was no contact or closeness between spectators and players or staff members. Several players and staff members developed COVID-19 earlier than the others, so they must have been infected before the Games. It was presumed that virus-containing aerosol released from infected players on the ice rink floated to the seats of the spectators and some spectators were infected.

The amount of virus an infected person releases differs widely with a person's metabolic rate and with or without a cough [24,25]. A person's metabolic rate differs with his or her physical activity, and an ice hockey player's metabolic rate in a game is supposed to reach nearly ten times as high as that at rest [26]. Regarding studies on ice hockey masks, Shaw et al. conducted a randomized cross-over study to assess the effect of wearing face masks on performance in youth hockey players, concluding that mask-wearing had no significant impact on performance or physiological parameters [27]. Critelli et al. explored the impact of wearing face masks on the lower visual field in youth hockey players, finding that mask-wearing obstructed vision and could compromise safety during play [28]. Although there is a divergence of opinion on this matter, the players and the referees did not wear facial masks at the Games.

For reference, an ice hockey game is played in three 20 min periods with two 15 min intervals during which ice making is conducted by ice resurfacers. In Kushiro Ice Arena, electric ice resurfacers are used.

### *2.2. Building Overview*

Kushiro Ice Arena is 2-storied building of reinforced concrete construction built in 1996. Its building area is 6663 $m^2$, its floor area is 7564 $m^2$, and its seating capacity is 3739 (2539 seats and 1200 standings). It has an ice hockey rink that measures 60 m by 30 m in size.

There are benches for players on the west side and an officials bench on the east side. The ice rink is surrounded by opaque walls and transparent protective panels. These walls and panels protect spectators from hockey pucks. The opaque walls around the ice rink are 1.07 m high from the surface of the ice and the transparent protective panels are 1.8 m high on the east side (side line) and 2.4 m high on the south and north sides (end line).

Figure 3 shows cold airflow from the ice rink to the player benches. There is no protective panel near the player benches on the west side and our smoke test proved that cold air on the ice rink spreads out of the player benches. On the other hand, there are

protective panels on the east side. The doors of the goal storage space near the officials bench were closed during the Games and the smoke leakage from the door gaps was not recognized in the smoke test.



**Figure 3.** Cold airflow from the ice rink to the player benches.

Figure 4 shows the air-conditioning and ventilation system. Two air handling units (AHU) are set on the north side on the second floor. Supply air is provided diagonally downward from the nine circle inlets (350 mm diameter) of each of two ducts (900 mm diameter) near the ceiling on the west and east sides of the ice rink to the central part of the ice rink. There are two vents on the north side of the passage on the second floor and they are connected to AHU. There are six fans near the ceiling. The designed ventilation rates are as follows: outside air rates (OA) are 12,000 $m^3/h$, supply air rates (SA) are 42,000 $m^3/h$, and exhaust air rates (EA) are 12,000 $m^3/h$. OA is equivalent to required ventilation rates for 400 persons.

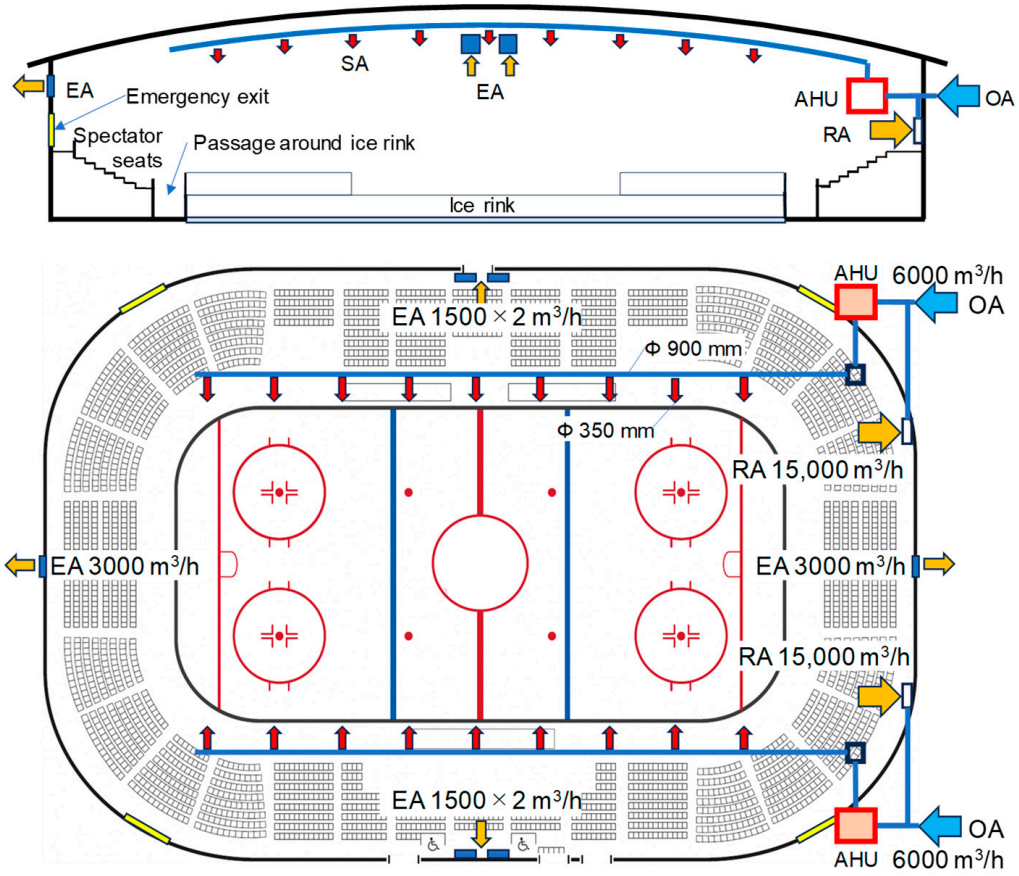



**Figure 4.** Air-conditioning and ventilation system.

### *2.3. Verification Method Overview*

#### 2.3.1. Ventilation Characteristics

In order to verify the ventilation characteristics of the ice arena, $CO_2$ was generated from a gas cylinder in the ice rink for 5 min. Since the measurements were conducted in a cold environment, particularly the utilization of liquefied carbon dioxide gas to discharge $CO_2$ throughout the ice rink, a multitude of gas cylinders were employed, and meticulous attention was paid to prevent freezing. When the $CO_2$ concentration at 1.6 m high became more than 1000 ppm at every measurement point (14 kg of $CO_2$ in total), ventilation frequency at every point was calculated based on the $CO_2$ concentration decline thereafter. The $CO_2$ concentration decay method was based on the "The Society of Heating, Air-Conditioning and Sanitary Engineers of Japan (SHASE) standard [29]". This method of using $CO_2$ related to COVID-19 has been used in several scientific papers, including [30–33], and has also been proposed as a potential modification to the existing method [34].

Measurements were taken under the same conditions of operation of the air-conditioning and ventilation system as that of the infection outbreak as well as when indoor temperature was steady. As shown in Figure 5, eleven measuring instruments (T&D TR-76U) were set up in and around the ice rink. They were situated in the vicinity of the spectator seats on the west side near the player benches, where the positivity rates were high, and were placed directly on top of the seats. Temperature, humidity, and $CO_2$ concentration were continuously measured for 10 s. The accuracies of these measurements are temperature ± 0.5 °C, humidity ± 5%RH, and $CO_2$ concentration ± 50 ppm ± 5% of reading.

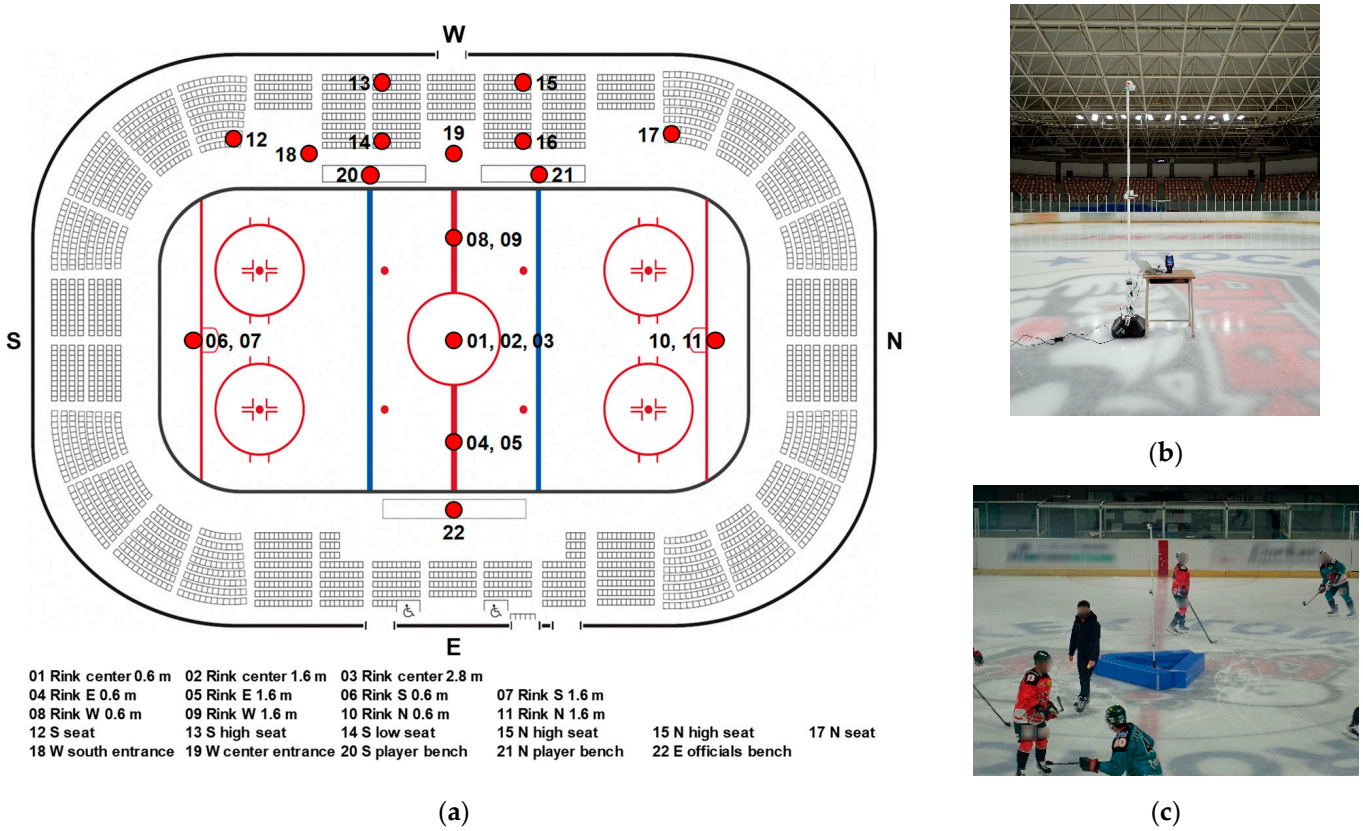



**Figure 5.** Measurement points: (**a**) Floor plan; (**b**) center of the ice rink; (**c**) reproduction of ventilation characteristics at the outbreak of infection.

#### 2.3.2. Aerosol Diffusion Characteristics

In order to verify the aerosol diffusion characteristics created by the players' movements in the Games, the particles from a smoke generator (Sharelife 400 W, Antari FLR-5) were generated on the ice rink. The amount of smoke was 6000 cu ft/min and the distance

of smoke was 9.8 feet. After the particles spread all over the ice rink, a one-period game was played by professional ice hockey players. The particle concentration at measurement points were continuously measured (Watty HYPM PM2.5 sensor, Table 2) for 1 min. As the measurements were taken during a game, only the center of the ice rink was set up inside the ice rink, to the extent that it did not interfere with play. The ventilation frequency was calculated using the same concentration decay method as for $CO_2$, focusing on data outside the ice rink. Due to the limited conditions known under the COVID-19 pandemic, the number of measurements on ventilation characteristics and aerosol diffusion characteristics was limited to one each.

**Table 2.** PM2.5 sensor specification.

| CH | Range | Accuracy |
|---|---|---|
| 1 ch | 0.3 μm to 1.0 μm | 1 ch to 4 ch common |
| 2 ch | 0.3 μm to 2.5 μm | 0 to 100 μg/m$^3$: ±10 μg/m$^3$ |
| 3 ch | 0.3 μm to 4.0 μm | 100 to 1000 μg/m$^3$: ±15% |
| 4 ch | 0.3 μm to 10.0 μm | at 10 °C or below |

## 3. Results and Analysis

### *3.1. Ventilation Characteristics*

Figure 6 shows the temperature at the measurement points. There was about a two-degree temperature difference between the lower part (0.6 m above the ice rink) and the upper part (2.8 m above the ice rink). The temperature at the south player bench was almost the same as that as the middle part (1.6 m above the ice rink) but that of the north player bench was higher. The temperatures at the officials bench and the west entrances were relatively high, ranging from 6 °C to 7 °C, and those at the spectator seats were also relatively high, at over 7 °C.

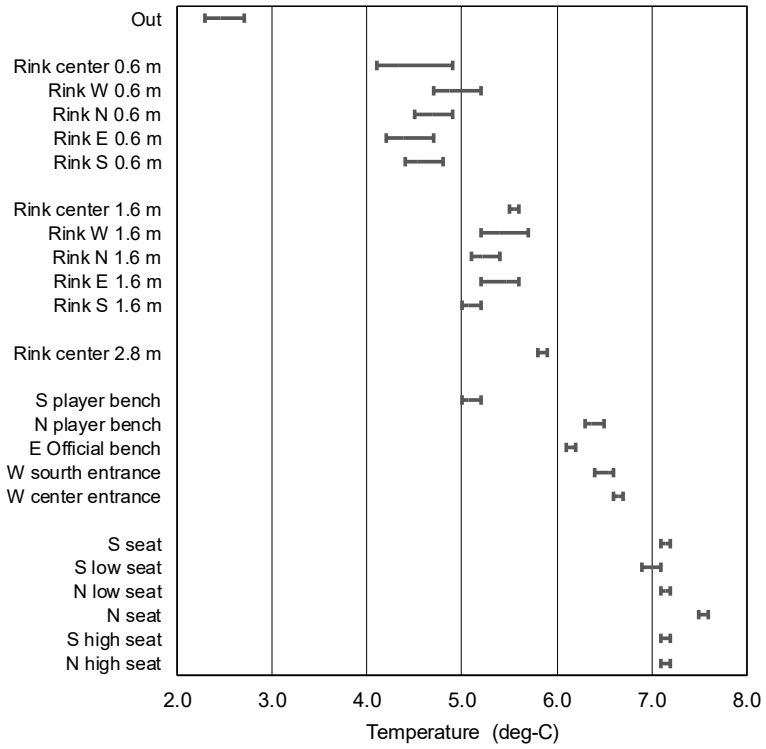



**Figure 6.** Temperature at measurement points.

Next, as shown in Figure 7, the $CO_2$ concentration at the center of the ice rink reached 2000 ppm at 0.6 m above the ice rink but about 700 ppm at 2.8 m above the ice rink. The

$CO_2$ concentration at 1.6 m above the ice rink was lower than that at 0.6 m above the ice rink at every measuring point. On the other hand, the $CO_2$ concentrations at the player benches were almost the same as those at 1.6 m above the ice rink, and the $CO_2$ concentration at the south player bench was higher for most of the time than that at the north player bench. The $CO_2$ concentrations at the officials bench and the west entrances were lower than those at the player benches. The $CO_2$ concentrations at the spectator seats were under 800 ppm and lower than those at the ice rink, the player benches, and the west entrances. The order of high $CO_2$ concentration space was the lower part (0.6 m above the ice rink), the player benches, the middle part (1.6 m above the ice rink), the west entrances, and the spectator seats.

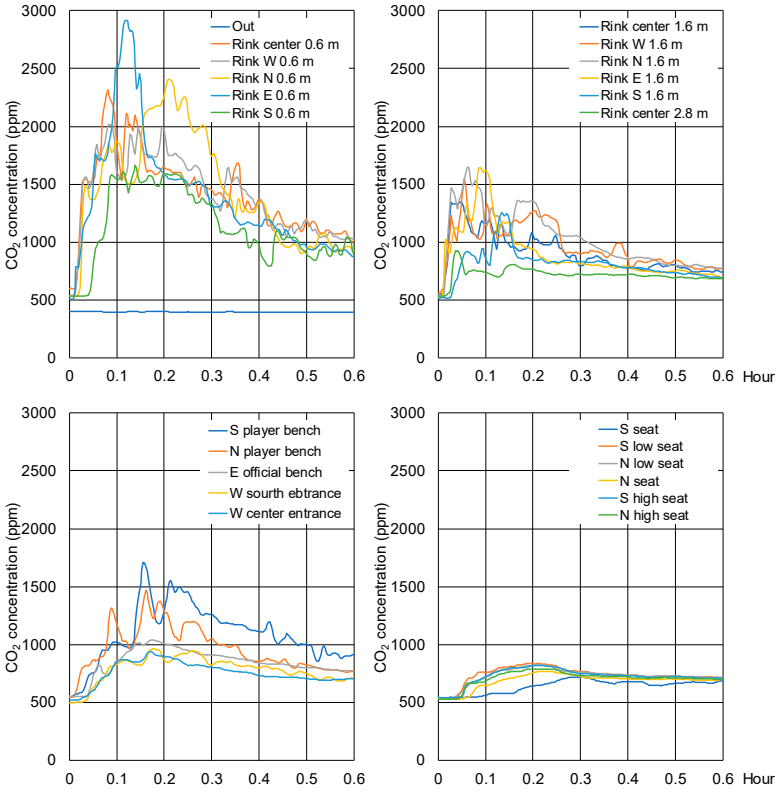



**Figure 7.** $CO_2$ concentration at measurement points.

Figure 8 shows the ventilation frequency calculated from $CO_2$ concentration decline from 0.25 h to 0.45 h in Figure 7. Under the condition that there was a $CO_2$ concentration difference between places in one large space, the ventilation frequency was calculated from $CO_2$ concentration decline caused by the difference between $CO_2$ inflow and outflow at each measurement point. The ventilation frequency at the lower part (0.6 m above the ice rink) was the most; 2.3 times/h at the east part and from 1.2 times/h to 1.4 times/h at the other parts. The ventilation frequency at the upper part (2.8 m above the ice rink) was 0.5 times/h and fewer than those 0.6 m high and 1.6 m high. The ventilation frequencies at the player benches were 1.4 times/h and 2.1 times/h, which was not so different from those 0.6 m and 1.6 m above the ice rink. The ventilation frequency at the officials bench was 0.9 times/h, which was almost the same as the middle part (1.6 m above the ice rink). The ventilation frequencies at the west entrances were 0.4 times/h at the north part and 1.6 times/h at the south part. The ventilation frequency at the south part was more than the north, and this tendency was also seen at the player benches. In contrast, the ventilation frequencies at the spectator seats were few, from 0.0 times/h to 0.3 times/h. Therefore, considering the $CO_2$ concentration decline shown in Figure 7, it was concluded that cold air in the ice rink flowed through the player benches and the west entrances to the spectator seats and stayed there in some degree.

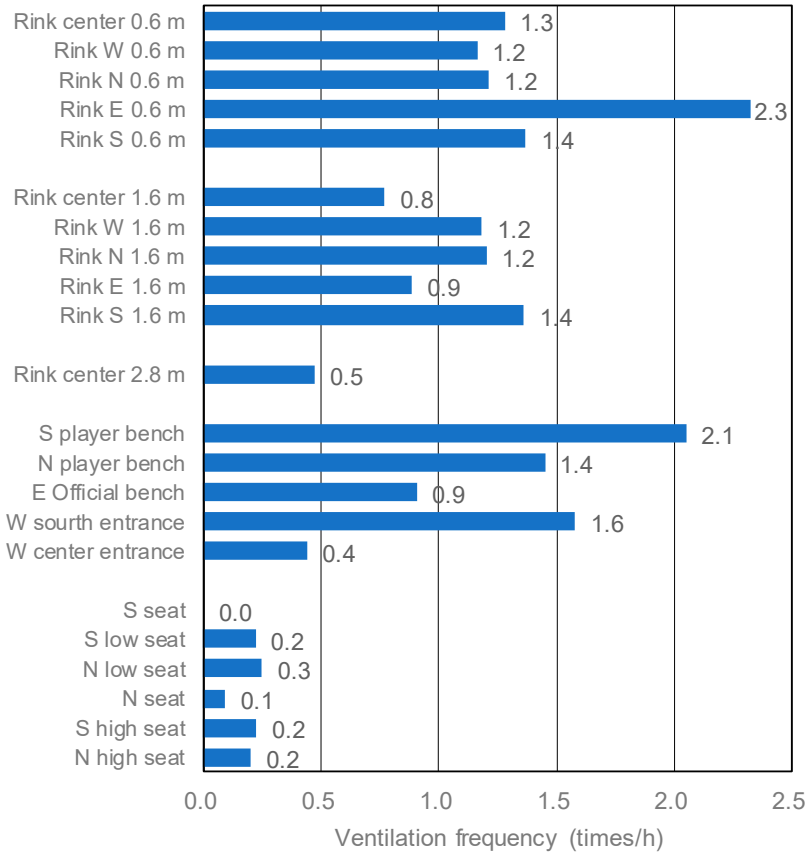



**Figure 8.** Ventilation frequency using $CO_2$ concentration.

### *3.2. Aerosol Diffusion Characteristics*

Figure 9 shows particle concentration for a one-period game by professional ice hockey players. In accordance with the smoke generation, the particle concentration was higher at the south entrance and at the player benches, and after that, the particle concentration at the central entrance became higher. At the spectator seats, it was confirmed that particles were flowing before the game. The peak of the particle concentration was seen after 0.1 h and the decline was seen after 0.2 h. Smoke generation was stopped, and a one-period game was played for 20 min from 0.27 h to 0.6 h.

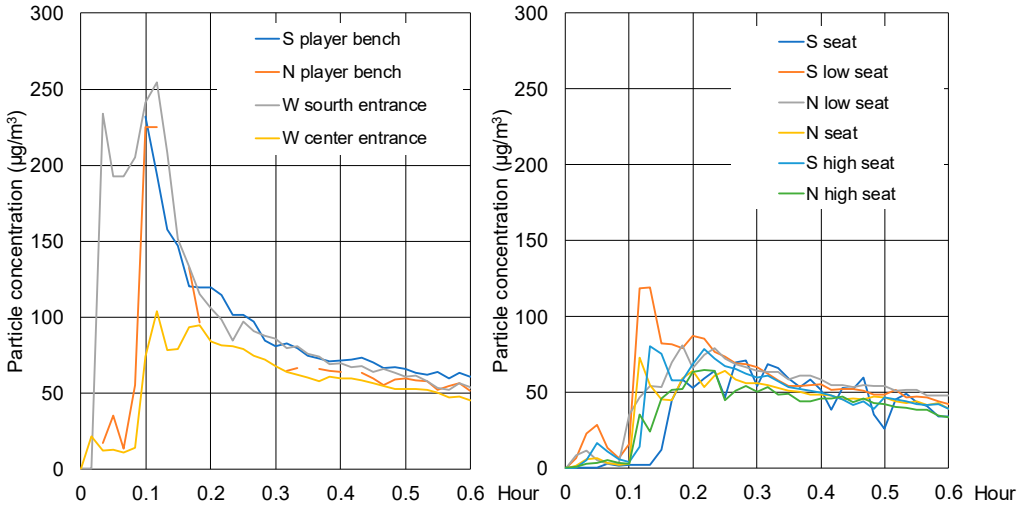



**Figure 9.** Particle concentration for a one-period game.

Figure 10 shows the ventilation frequency calculated from particle concentration decline during the game. The ventilation frequencies at the player benches and the west entrances were from 0.9 times/h to 1.6 times/h. They were not so different from $CO_2$ concentrations calculated while a game was not being played (Figure 8). However, the ventilation frequencies at the spectator seats were from 1.1 times/h to 1.6 times/h and they were much higher than those from $CO_2$ concentration. This difference contrasted with the stable and accumulated cold air conditions, where aerosol diffusion into the spectator seats was facilitated by adding the players' movements. It was presumed that this results in air circulation in the upper and lower layers, thereby expediting the decline in particle concentration at the spectator seats.

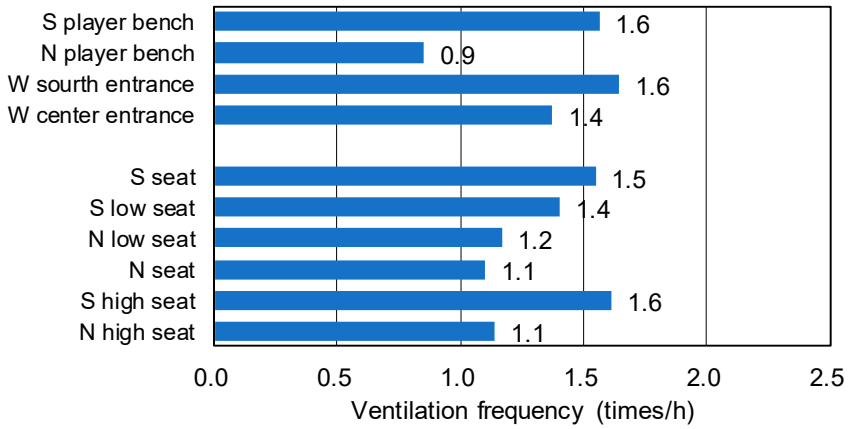
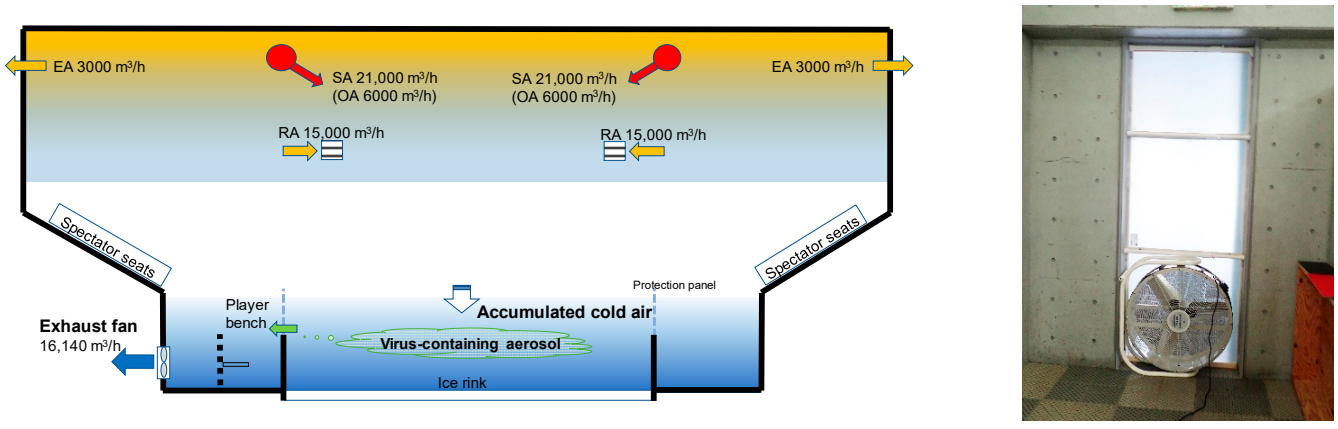



**Figure 10.** Ventilation frequency using particle concentration.

### *3.3. Ventilation Measures against COVID-19 Transmission through the Air*

#### 3.3.1. Measurement Conditions

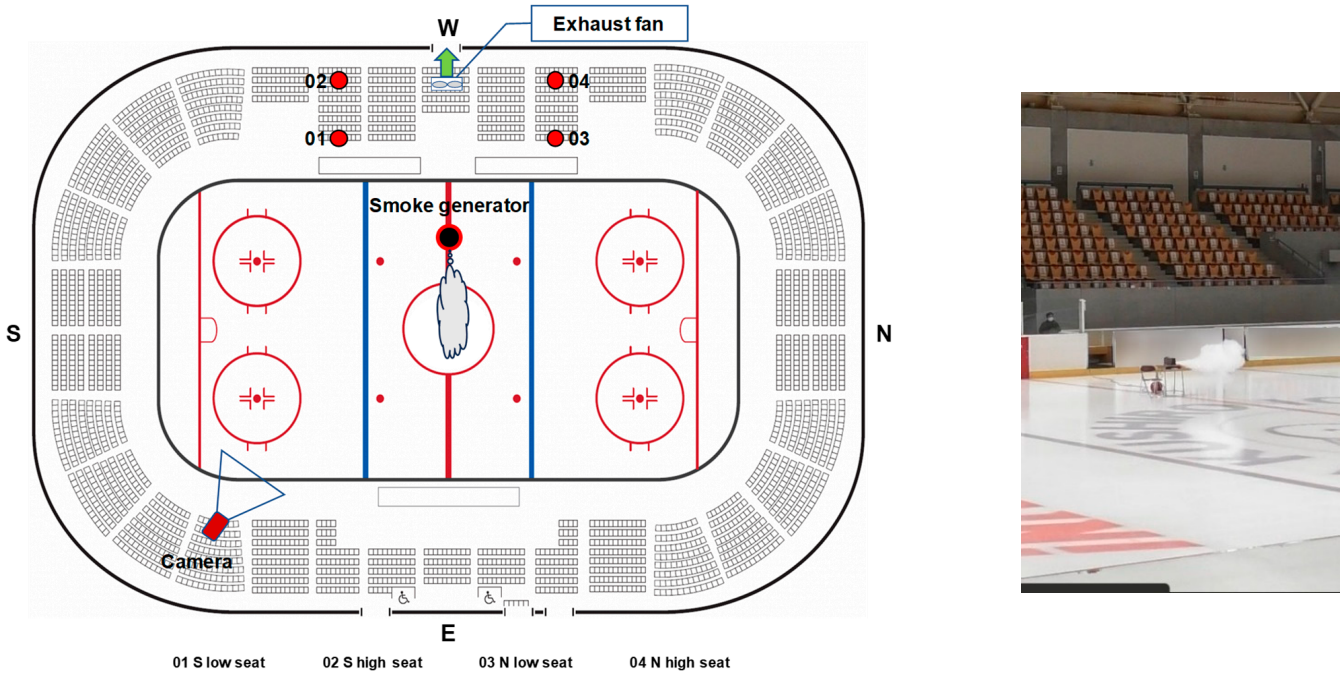
A way of preventing the outbreak of infection by controlling virus-containing aerosol diffusion was verified and the following ventilation measures was designed. As shown in Figure 11, an exhaust fan was set at one of the player entrances to exhaust cold air staying in the lower part in the ice arena and to control virus-containing aerosol spread from the ice rink to the spectator seats. In order to verify the effects of the ventilation measures, the aerosol diffusion characteristics were measured under two conditions. The conditions were whether the exhaust fan with an airflow rate of 16,140 $m^3$/h was off or on. Fan off was same condition as during the Games. The exhaust fan was operated carefully to avoid short circuits in the airflow.




(**a**) (**b**)

**Figure 11.** Ventilation measures: (**a**) cross-section; (**b**) exhaust fan.

As shown in Figure 12, particles were released from a smoke generator set 0.8 m high at the center of the ice rink, and the number of particles at the measurement points were counted (Kanomax Japan Inc., Model 3889 particle counter, Table 3). Under fan off, smoke was generated for 5.0 min at first and for 3.5 min under fan on.




(**a**) (**b**)

**Figure 12.** Measurements points: (**a**) floor plan; (**b**) smoke generator.

**Table 3.** Particle counter specification.

| | **Compliant with JIS B9921 [35] and ISO21501-4 [36]** |
|---|---|
| Size | 6 CH (0.3, 0.5, 1.0, 3.0, 5.0, 10.0 μm) |
| Flow Rate | 2.83 L/min (accuracy ± 5%) |
| Counting Efficiency | 50 ± 20% (for polystyrene latex particles near the minimum measurable size) |
| False Count | Less than 1 particle/5 min |

### 3.3.2. Results of Measures

Figure 13 shows the visualization of particle dispersal. When the images at 16 min after smoke stopped were compared, the smoke on the ice rink moved in the following ways: Under fan off, the smoke stayed on the north part of the ice rink, while the smoke stayed at the lower layer all over the ice rink under fan on. In the spectator seats, the smoke stayed under fan off. These results of visualization showed that under fan off, the smoke on the ice rink spread to the spectator seats, and the exhaust fan prevented smoke from going upward to the spectator seats.

Figure 14 shows particle concentrations under fan off and on, indicateing the mean and standard deviation of concentration for 16 min after the smoke generation. The concentration values in the Figure are the total numbers of particle size from 1.0 μm to 10.0 μm. Similar to the particle visualization, fan off clearly had a higher particle concentration, especially on the south side. Fan on temporarily increased the particle concentration in the low seat on the south side, but overall values and variability of particle concentration were decreased.




(**a**)



(**b**)

**Figure 13.** Visualization of particle dispersal: (**a**) fan off; (**b**) fan on.

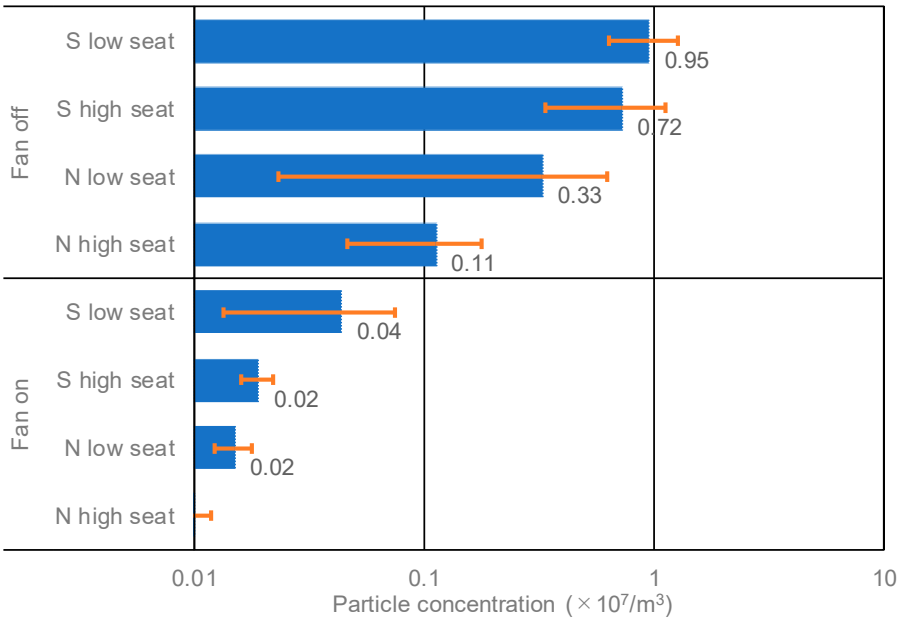



**Figure 14.** Particle concentrations under fan off and on.

As shown in Table 4, the normalized particle concentration in the table means that mean particle concentration under fan on was multiplied by 1.42 because the release time of smoke under fan off was 1.42 times as long as that under fan on. The normalized particle concentration became low when the exhaust fan was operated. Compared with fan off, the normalized particle concentration under fan on was only 6%, so the exhaust fan was proved to be effective at keeping the smoke from the spectator seats.

**Table 4.** Effect of exhaust fan.

| Fan | Release Time of Smoke | Mean Particle Concentration for 16 min after Smoke Stopped | Normalized Particle Concentration Using Release Time Based on Fan Off | Ratio to Fan Off |
|---|---|---|---|---|
| Off | 5.0 min | $0.528 \times 10^7/m^3$ | $0.528 \times 10^7/m^3$ | 100% |
| On | 3.5 min | $0.022 \times 10^7/m^3$ | $0.031 \times 10^7/m^3$ | 6% |

From the above results, the exhaust from a fan is expected to prevent virus-containing aerosol on the ice rink from spreading to the spector seats. On the other hand, inlets for air supply are necessary to exhaust indoor air using a fan. When the wind is strong, the inflow of outdoor air makes indoor airflow change and possibly affects aerosol diffusion. This suggests the need to consider the outdoor air environment and design an effective way to bring in outdoor air in conjunction with ventilation measures.

## 4. Limitations

Regarding the epidemiological findings, there are at least two limitations for interpretation. First, the authors could not identify the exact dates for watching for some spectators, and we excluded these people from analysis. Second, we could not identify possible exposures other than watching the Games, and the infected cases may have been infected at other opportunities.

On the other hand, the differences between the actual conditions at the outbreak of infection and measurement conditions are as follows. First, when the outbreak of infection occurred, ice-making trucks were used at intervals and they were supposed to stir up air on the ice rink. Second, when the players and the spectators entered or exited the ice arena, the indoor airflow near entrances or in the ice arena was supposed to change. Therefore, virus-containing aerosol moved from the ice rink to the spectator seats and the diffusion at the spectator seats was probably more remarkable than the results of the measurement.

In the verification of the ventilation measures against COVID-19 transmission through the air, an exhaust fan was set in the low part of the west side to prevent aerosol diffusion from the ice rink and player benches to the spectator seats. Smoke was used in the verification, and a significant effect was recognized. However, there is a possibility that air stirred by players' movements in the game, ice-making, spectators' movements and other environmental conditions could affect the effect of an exhaust fan.

Consequently, the findings are not universally applicable to all other environments because this study presents ventilation measures for a specific ice arena in Japan. It is essential to carefully consider the suitability of additional measures to the existing ventilation system in terms of their installation location and the required airflow. However, one common point is that the prevention of infection among spectators necessitates the establishment of a system to exhaust sufficient air from a lower-level in the ice arena and uniform ventilation with fans and circulators. Furthermore, it is also crucial to minimize the amount of time spectators spend unmasked and to promote the appropriate use of non-woven masks by spectators. It is also imperative to broaden the perspective further, and to restructure the control of existing air-conditioning and ventilation systems by integrating them with studies [37,38] addressing the use of wearable devices during a pandemic in the future.

## 5. Conclusions

In this study, a COVID-19 outbreak and ventilation measures against COVID-19 transmission through the air occurred at an ice arena in Japan, categorized as a specific entertainment place, were discussed. The findings obtained are as follows:

1. Through epidemiological investigation, out of the 172 infected persons, it was determined that 102 spectators and all 42 players were infected. The virus was classified as the Omicron variant (BA.1.1.2) by genomic analysis. It was presumed that some

spectators were infected by virus-containing aerosol released from infected players on the ice rink.

2. It was revealed that cold air in the ice rink flowed through the player benches to the spectator seats using $CO_2$ particles as a tracer gas. The ventilation frequencies at the spectator seats were calculated to be 0.0 times/h to 0.3 times/h based on $CO_2$ concentration during a non-game, but from 1.1 times/h to 1.6 times/h based on particle concentration during a game. The difference can be attributed to the aerosol diffusion into the spectator seats, which was facilitated by adding the players' movements.
3. The results of ventilation measures implemented in response to the possibility of COVID-19 transmission through the air confirmed that the normalized particle concentration under fan on was only 6% compared with fan off. The integration of a lower-level exhaust fan based on cold air characteristics into the existing ventilation system was highly effective at the spectator seats.

The condition of an ice arena is unique due to the maintenance of ice on the ice rink, the prevention of vapor condensation, blur on the transparent protective panels, and so on. Therefore, in operating air-conditioning and ventilation system, the maintenance of steady air in the ice rink is a main priority. Under this unique air-conditioning and ventilation system, virus-containing aerosol released from a player in the ice rink accumulated in the cold air spot. It was highly possible that the outbreak diffused from the player benches without protective panels to the spectator seats in the Games. Judging from this outbreak of infection which included spectators through this study by integrating epidemiological and engineering approaches, the possibility of COVID-19 transmission through the air cannot be ruled out.

**Author Contributions:** Conceptualization, K.K. and M.H.; validation, K.K. and M.H.; formal analysis, K.K., S.O., T.Y. and M.H.; investigation, all authors; writing—original draft preparation, K.K., S.O., T.Y. and M.H.; writing—review and editing, all authors; funding acquisition, M.H. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was supported by MHLW Grant Number JPMH21LA1005.

**Informed Consent Statement:** This report was exempt from the requirement for institutional ethics review because it was part of a public health response by local governments, and we did not obtain informed consent from the cases at the time of investigation. However, we consulted the ethical committee of the National Institute of Infectious Diseases and the committee approved the secondary use of the data obtained during the outbreak investigation.

**Data Availability Statement:** The data used to support the findings of this study are available from the corresponding authors upon request.

**Acknowledgments:** This study was conducted by Hokkaido University, Kushiro Public Health Center, the Hokkaido Government Department of Health and Welfare, the Hokkaido Institute of Public Health, and the National Institute of Infectious Diseases in cooperation with Kushiro City, Kushiro Sports Promotion Foundation, the Kushiro Ice Hockey Federation, the Japan Ice Hockey Federation, the Asia League Ice Hockey Japan Office and people from the two ice hockey teams concerned. The authors would like to express their appreciation for all those who assisted. Additionally, this study was conducted by integrating epidemiological and engineering approaches, and S.O. made a significant contribution to field of epidemiology.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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