Tokai J Exp Clin Med., Vol. 48, No. 2, pp. 62-66, 2023

Risk of Sports-associated Long-range Airborne Transmission of SARS-CoV-2: A Mathematical Modeling Study

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(Received February 7, 2023; Accepted March 30, 2023)

Objective: The worldwide pandemic caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and its variants remains a health threat. As sports event-related outbreaks due to long-range airborne transmission in ventilation have been reported, the present study aimed to quantify infection risk using available data and apply the results to an outbreak in an ice hockey arena.

Methods: A mathematical modeling approach was used to estimate the risk of airborne infection.

Results: A quantum was defined as the dose of airborne droplet nuclei required to cause infection in 63% of susceptible persons. The estimated quanta emission rate per infector showed a log-normal distribution with a geometric mean (GM) of 28.81, geometric deviation (GD) of 5.78, and median of 22.65 quanta/h. The estimated average time-average quanta concentration (C_{avg}; quanta/m^3) showed a log-normal distribution with a GM of 0.08, GD of 5.80, and median of 0.06. The outdoor ventilation rate per infected person for the scenario showed a log-normal distribution with a GM of 710.96, GD of 6.22, and median of 169.17 m^3/h. A higher C_{avg} value indicated exposure to SARS-CoV-2 due to the lower ventilation rate in the arena and the large expiratory volume of athletes caused by intensive exercise.

Key words: SARS-CoV-2, mathematical model, ice hockey arena, cold pool, air ventilation

INTRODUCTION

Since the beginning of the coronavirus disease 2019 (COVID-19) pandemic, discussions about the transmission routes of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) have been ongoing. It has been accepted that transmission occurs through the direct and "short-range" (1–2 m) spread of respiratory droplets. It is also considered that airborne transmission over longer distances may occur via virus-containing aerosols. Outbreaks of COVID-19 associated with ice hockey games have been reported in the United States and Japan [1–3]. From the report of an outbreak at the 2022 Asia League Ice Hockey game held on January 15–16 in Hokkaido, Japan, 172 cases of COVID-19 were confirmed, 102 (59%) of whom were spectators [3]. Most of the cases involving spectators were reported in those seated behind the players' benches, and there were no opportunities for many spectators to be in contact with each other at close range. The spectators were seated at intervals, could eat and drink at their seats, and were required to wear masks when not eating or drinking [3]. Therefore, long-range airborne transmission of SARS-CoV-2 was highly suspected as a cause of this outbreak among spectators.

Given this background, the present study aimed to evaluate the risk and clarify the characteristics of long-range airborne transmission of SARS-CoV-2 using a mathematical modeling approach.

MATERIAL AND METHODS

Model framework

The model of infection risk used in the present study was based on the Wells–Riley model [4], as amended by Gammaitoni and Nucci [5] and Kurnitski *et al.* [6]. In the Wells–Riley model, the probability of infection for susceptible persons (p) was given by the following:

$$p = \frac{N_c}{N_s} = 1 - e^{-n} \tag{1}$$

where N_c is the number of disease cases, N_s is the number of susceptible persons in the room, and n is the inhaled quanta. A quantum was defined as the dose of airborne droplet nuclei required to cause infection in 63% of susceptible persons [4].

The inhaled quanta (n) depends on the time-average quanta concentration (C_{avg}; quanta/m^3), volumetric breathing rate of the occupant (Q_b; m^3/h), and duration of the occupancy (D; h). If wearing a mask with efficiency η_s for a susceptible person reduces the number of quanta inhaled, n is given as:

$$n = C_{avg} \bullet Q_b \bullet (1-\eta_s) \bullet D \tag{2}$$

The airborne quanta concentration increases with time from an initial value of 0 following a "one minus exponential" form, which is the standard dynamic response of a fully-mixed indoor volume to a constant source. A single-zone fully-mixed material balance

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model for the room is applied to calculate the concentration as follows:

$$\frac{dC}{dt}=\frac{E}{V}-\lambda C \quad (3)$$

where E is the quanta emission rate (quanta/h), V is the volume of the room (m^3), λ is the first-order loss-rate coefficient for quanta/h due to the summed effects, deposition onto surfaces (λ_{dep}; 1/h), and virus decay (k; 1/h), and C is the time-dependent airborne concentration of infectious quanta (quanta/m^3). The quantum emission rate E is the product of the number of infected persons I and the value q (quanta/(h person)) of the quanta emission rate per infected person.

Thus, E for an infected person without a face mask is described as:

$$E=Iq$$

Assuming the quanta concentration is 0 at the beginning of the occupancy, equation (3) is solved and the average concentration is calculated as follows:

$$C(t)=\frac{E}{\lambda V}(1-e^{-\lambda t}) \quad (4)$$

where t (h) is the time in exposure periods.

$$C_{avg}=\frac{1}{D}\int_0^D C(t)dt=\frac{E}{\lambda V}\left[1-\frac{1}{\lambda D}(1-e^{-\lambda D})\right] \quad (5)$$

From (1), (2), and (5), the following expression is derived:

$$p=1-\exp\left(\frac{IqQ_b\cdot(1-\eta_s)\cdot D}{Q+(\lambda_{dep}+k)V}\right) \quad (6)$$

where Q (m^3/h) is the outdoor air ventilation rate [6].

Solving equation (6) for Q gives the following expression [6]:

$$Q=\frac{IqQ_bD}{\ln\left(\frac{1}{1-p}\right)}-(\lambda_{dep}+k)V$$

From this result, the required outdoor ventilation rate per infected person for a given probability of infection and quanta emission rate can be estimated.

The overall risk of infection was calculated using the Monte Carlo simulation with probability distributions for the input parameters. A total of 10,000 simulations were conducted. All analyses were performed using Microsoft Excel 2010 (Microsoft Corp., Redmond, WA) and Crystal Ball™ software (Oracle Corp., Redwood Shores, CA). The Anderson–Darling statistic was used as a test-of-fit for the distributions.

Parameters

Regarding the spectators' inhalation of quanta, the volumetric breathing rate (Q_b; m^3/h) of a spectator was 1.1 m^3/h as the activity involving only talking [7, 8], and the face mask efficiency η_s for a spectator was 0.3 [9]. As for the quanta emission, the quanta emission rate q was given, of which, $\log_{10}q$ had a log-normal distribution, with a mean of 1.50 and standard deviation (SD) of 0.72 [10]. The number of infectors was four players who belonged to the same team, and who tested positive for COVID-19 on January 16, 2022. As for the virus deposition rate onto surfaces, λ_{dep} was set to 0.3 1/h [11, 12], and the virus loss rate k due to virus inactivation was set to 0.32 1/h [6, 13]. The rate of positive SARS-CoV-2 tests for spectators who were seated behind the players' benches was adopted as the probability p of infection, and p = 41/150 ≈ 27.3% (see **Appendix**). The values of these parameters are summarized in Table 1.

Simulation scenarios

Members of Hokkaido University, the Hokkaido government, and the National Institute of Infectious Diseases investigated the air flow on the ice rink and found that the cool air near the ice and the warmer air aloft created a thermal inversion that could restrict air movement in the arena [3]. Using a smoke test, they also observed that stagnant air on the ice rose up through the stands at a slope toward the upper exit

Table 1 Values of the parameters used in the simulation.

Parameter	Distribution		Mean	SD	Source
$\log_{10}q$	Log-normal distribution		1.50	7.20×10^{-1}	[10]
	Point value	Unit			Source
I	4				[3]
V	911.28	m^3			Appendix
D	3	h			
p	0.248				
Q_b	1.1	m^3/h			[7, 8]
λ_{dep}	0.3	1/h			[11, 12]
k	0.32	1/h			[6, 13]
η_s	0.3				[9]

SD: standard deviation.

Table 2 Results of the simulation for both scenarios.

	Sports facility [17]	This study
Infection probability (3 h)	0.257	0.273
Quanta emission rate (quanta/h)	21.0	22.65
C_{avg} (quanta/m^3)	0.03	0.06
Q (m^3/h)	540	169

over the course of 16 min. Based on the sizes of the competition (55 m × 91.4 m) and seating areas, the pooled volume of cold air above the seats was calculated (Figs. 1A and 2A in the **Appendix**). The duration of occupancy, including game time, was assumed to be 3 h, and the spectators who sat in the seats in areas A and B behind the players' benches (Fig. 1A) on January 16, 2022, were assumed to be most susceptible to infection, even though they were wearing face masks.

RESULTS AND DISCUSSION

Mathematical models used so far for modeling airborne transmission risk have been classified in two main parts; 1) Wells-Riley and dose-response models and 2) computational fluid dynamics (CFD) model [14, 15]. As CFD modeling requires expertise knowledge and long-time numerical calculation, it is difficult for public health experts to use CFD model to estimate the infection risk from the epidemiological data. And a validated dose-response model for SARS-CoV-2 was currently not available [14]. Therefore, modified Wells-Riley model was used for feasible infection risk estimation in this study, and the time-average quanta concentration and outdoor ventilation rate were estimated based on epidemiological data and airborne infection risk parameters previously reported.

The estimated quanta emission rate per infector showed a log-normal distribution with a geometric mean (GM) of 28.81, geometric deviation (GD) of 5.78, and median of 22.65 quanta/h. The estimated time-average quanta concentration (C_{avg}; quanta/m^3) showed a log-normal distribution with a GM of 0.08, GD of 5.80, and median of 0.06.

The outdoor ventilation rate per infected person for the scenario showed a log-normal distribution with a GM of 710.96, GD of 6.22, and median of 169.17 m^3/h.

Duval *et al.* [16] reviewed 22 reports from 18 studies to evaluate the potential for the long-distance airborne transmission of SARS-CoV-2 in indoor community settings. In that review, the transmission settings included singing events, apartment blocks, quarantine hotels, restaurants, buses, a food processing facility, a courtroom, a department store, and a fitness facility. The duration of exposure was between 5 min and 3 h, and involved distances of up to 15 m. They found that the factors most likely contributing to long-distance airborne transmission were insufficient air replacement, directional air flow, and activities associated with increased aerosol emission.

COVID-19 clusters associated with an ice hockey game have been reported. Atrubin *et al.* [1] reported that 14 team members and one rink staff member tested positive for COVID-19 infection by the Florida Department of Health after an evening hockey game on June 16, 2020 in the USA. A COVID-19 outbreak related to the 16th national high school selection ice hockey tournament held in Hokkaido, Japan on August 4–8, 2021 was also reported [2]. In total, 150 cases were identified as COVID-19-positive; 132 of the 150 were players who were in close contact during the game (e.g., on the ice, on the bench), before and after the game (e.g., changing clothes in the locker room, in the corridor), and during activities held throughout the tournament. Similarly, at the 2022 Asia League Ice Hockey game held on January 15–16 in Hokkaido, Japan, 172 cases were confirmed as COVID-19-positive, and the percentages of positive SARS-CoV-2 cases were 55/59 (93%) among athletes and team personnel, 15/76 (20%) among tournament-related personnel (e.g., referees, journalists), and 102/867 (12%) among spectators [3]. As the spectators had little opportunity to come into close contact with the players, tournament officials, or each other, long-range airborne transmission was considered to be the main route of SARS-CoV-2 infection from the players to the spectators. Genomic analyses of samples from two team members, a tournament official, and spectators revealed that all samples were the same Omicron strain (B.1.1.529) [3].

In the present study, the median estimated quanta concentration around the seats in the stands was 0.06 quanta/m^3. Kurnitski [17] estimated the probability of infection in various scenarios involving nonresidential rooms, and found the highest probability of infection at 0.257, as well as a higher average quanta concentration (0.03 quanta/m^3), in the case of a sports facility with a 3 L/s m^2 (540 m^3/h with 150 m^3) ventilation rate for 3 h of occupancy time compared with other cases, as physical exercise increased the quanta emission and breathing rates (Table 2). This ventilation rate was equivalent to 3.6 air changes per hour (ACH), which is a popular setting in offices in Japan. In the present study, the probability of infection was similar to that in Kurnitski's report [17], but the median quanta concentration was higher, and the ventilation rate of 169.17 m^3/h with 911.28 m^3 (0.19 ACH) was much lower than that in his report.

Hayashi [18] investigated the air quality in the arena where the 2022 Asia League Ice Hockey game was held using a smoke test, and reported that outdoor air was only circulating in the upper layer of the arena, which suggests that ventilation for exhausting pools of cold air could be expected to reduce the risk of infection.

This study had several limitations. First, vaccine-induced immunity was not considered. Second, the actual airflow and environments differed from the values of the parameters. Despite these limitations, the results suggest that comprehending the ventilation conditions and related infection risk is necessary to improve air quality.

The area around the ice hockey rink was surrounded by a transparent wall called protective glass except in front of the players' benches to protect spectators from flying pucks. This protective glass obstructed the airflow and is thought to be one of the reasons why the virus-contaminated air remained on the ice. As a temporary control measure, it is conceivable to reduce the amount of virus-contaminated air that reaches the spectator seats by discharging the air that flows out from the front of the player's bench to the outside.

Rayegan *et al.* [14] reviewed indoor airborne transmission of COVID-19 modelling and mitigation approaches, and they investigated the ventilation with comparing natural and mechanical ventilations. The measures other than in front of the athletes' benches are desirable, and further environmental engineering measures will be necessary according to the situation of each facility and the limited energy and cost.

The use of face masks is also conditionally recommended based on the infection risk in environments where the air quality is insufficient.

ACKNOWLEDGMENTS

This work was partly supported by JSPS KAKENHI, grant No. 18K10013.

AUTHOR'S CONTRIBUTIONS

The author was solely responsible for the conceptualization, model calculation, and writing of this paper.

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Appendix

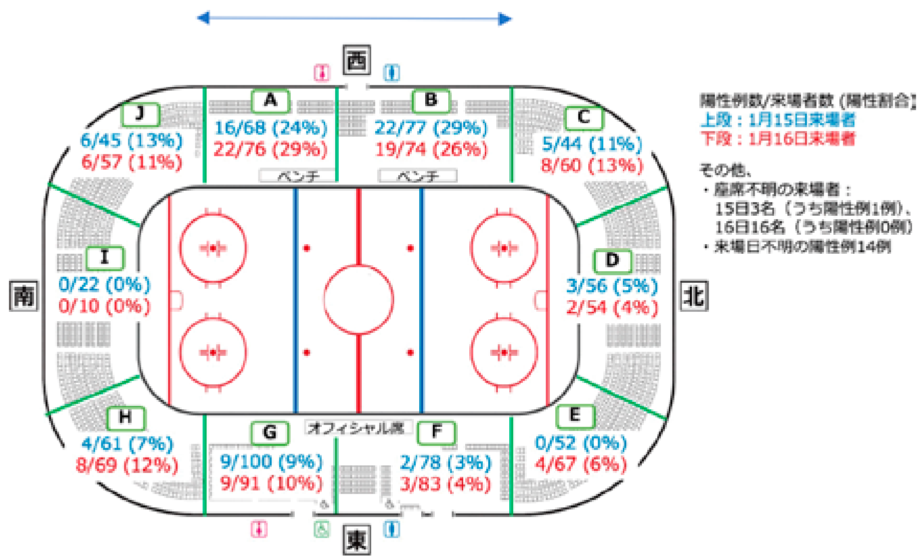

Fig. 1A Outline of the ice hockey arena and COVID-19 positivity rate in spectators. Blue numbers show the COVID-19 positivity rate in spectators on January 15, 2022, and red numbers show the positivity rate on January 16, 2022. The length of the long side of areas A and B is 74.9 m.

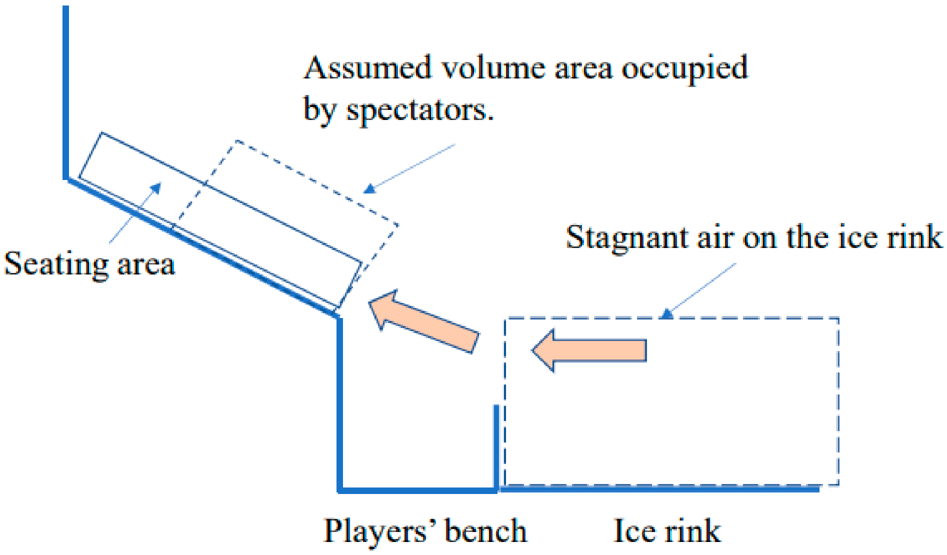

Fig. 2A Cross-sectional view of the seating area, air volume, and airflow in the ice hockey arena (based on [18]). The air volume area over the front two-thirds of the seating area was 1-m high and the surface area was 18.25 m^2 × 2/3. Thus, the total air volume was 18.25 m^2 × 2/3 × 74.9 m ≈ 911.28 m^3.
⇦ : indicates the direction of air flow from the ice rink to the seating area.