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# Response to COVID-19 during the Tokyo Olympic Games: Did we properly assess the risk?

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ABSTRACT

*Background:* The number of coronavirus disease 2019 (COVID-19) cases was expected to increase during the Tokyo Olympic Games because of the increased physical contact within and between the domestic population and international participants of the Games. The rapid rise of the Delta variant (B.1.617) in Japan meant that hosting the Olympic Games without any restrictions was likely to lead to an increase in cases. We aimed to quantitatively assess possible COVID-19 response strategies for the Olympic Games, comparing the prevalence of severe cases and the cumulative number of COVID-19 deaths via scenario analysis.

*Methods:* We used a discrete-time deterministic compartmental model structured by age group. Parameters were calibrated using the age-stratified COVID-19 incidence data in Osaka. Numerical simulations incorporated the planned Olympics Games and nationwide COVID-19 vaccination into the proposed model, alongside various subjects and types of countermeasures.

*Results:* Our model-informed approach suggested that having spectators at the Tokyo Olympic Games could lead to a surge in both cases and hospitalization. Projections for the scenario that explicitly incorporated the spread of the Delta variant (i.e., time-dependent increase in the relative transmissibility) showed that imposing stringent social distancing measures ($R_t$=0.7) for more than 8 weeks from the end of the Olympic Games might be required to suppress the prevalence of severe cases of COVID-19 to avoid overwhelming the intensive care unit capacity in Tokyo.

*Conclusions:* Our modeling analyses guided an optimal choice of COVID-19 response during and after the Tokyo Olympic Games, allowing the epidemic to be brought under control despite such a large mass gathering.

## 1. Introduction

In late February 2021, sporadic transmissions of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) Alpha variant (B.1.1.7) were first observed. Since then, the Alpha variant rapidly outcompeted preexisting variants in Japan because of its elevated transmission potential compared with wild types (Davies et al., 2021; Ministry of Health Labor and Welfare, 2021a). Despite public health and social measures (PHSMs) in the majority of affected areas, a rapid spread of the Alpha variant resulted in a “fourth wave” of the coronavirus disease 2019 (COVID-19) epidemic in Japan. By mid-April, there were 5000 new cases daily (Ministry of Health Labor and Welfare, 2021b). In response to the increase, the national government declared the third state of emergency (SoE) on 23 April 2021 in four urban prefectures where there had been an abrupt increase in incidence (i.e., Tokyo, Osaka, Kyoto, and Hyogo prefectures). They asked residents to limit non-household contact, for example, by refraining from going outside for non-essential reasons (Cabinet Relations Office, 2021a). This successfully suppressed the fourth wave of the epidemic. However, by the middle of June 2021, the country had experienced sustained SARS-CoV-2 transmissions, with less than 20 % of the population having been immunized with a single dose of COVID-19 vaccine (Cabinet Relations Office, 2021b).

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*Abbreviations:* CI, confidence intervals; COVID-19, coronavirus disease 2019; ICU, intensive care unit; IOC, the International Olympic Committee; PHSMs, public health and social measures; SARS-CoV-2, severe acute respiratory syndrome coronavirus 2; SoE, state of emergency.

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The worldwide spread of COVID-19 caused the International Olympic Committee (IOC) to postpone the Tokyo Olympic Games for 1 year from late July 2020. This 1-year postponement was originally suggested by the Japanese government, which hoped optimistically that the COVID-19 pandemic would have been brought under control at that time. However, by the start of 2021, there were no clear signs of decline in the incidence, and PHSMs were still being used to suppress transmission in Japan in the first half of 2021. Despite the struggle, the IOC insisted that the Tokyo Olympic Games should be held from 23 July to 8 August 2021, with the first event scheduled for 21 July 2021, before the opening ceremony. Around 69,000 international participants (including athletes, support staff, and news media) from over 200 countries were expected to gather during the Olympic period (Neal, 2021). Managing the risk of SARS-CoV-2 transmission related to the Olympic Games was actively debated both domestically and globally (Lancet, 2021; Murakami et al., 2021; Sparrow et al., 2021).

In response to these concerns, the IOC required stringent countermeasures such as frequent reverse transcription-polymerase chain reaction testing of participants and limiting interaction with people beyond Olympic venues. These were documented in the form of a “Playbook” (International Olympic Committee, 2021). Following several rounds of debates and recommendations from experts, both international and domestic spectators were banned to avoid transmission within venues and to minimize physical contact between the domestic population and Games participants. The national government also declared the fourth SoE from 12 July to 22 August 2021, covering the whole Olympic period (Cabinet Relations Office, 2021c). The countermeasures included prohibiting restaurants and bars from serving alcohol and requiring them to curtail their operations.

Despite huge debates in advance of the Games, SARS-CoV-2 transmission during the period remained unknown outside Japan. The Alpha variant was dominant in advance of the Games, but the Delta variant (B.1.617), which has been suggested to be more transmissible (Hester et al., 2021), began to emerge in Tokyo from around the middle of June 2021 (Ito et al., 2021). Despite the implementation of the fourth SoE, physical contact among the domestic population was considered likely to increase because of private gatherings before and during the Olympic Games. Given that human-to-human contact can accelerate the spread of new SARS-CoV-2 variants, it was recognized that hosting the Olympic Games without any restrictions would lead to an upsurge of severe COVID-19 cases, which might exceed the available hospital bed capacity in Tokyo. To avoid this, a tailored COVID-19 response strategy had to be considered. This was a political decision, but had to be guided by quantitative assessment, comparing different control measures and types of intervention.

To evaluate potential COVID-19 response strategies for the Olympic Games, we applied a model-informed approach to projecting COVID-19 transmission scenarios in Tokyo. Using the model, we made a comparative assessment of different combinations of interventions, investigating the potential prevalence of severe cases and the cumulative number of COVID-19 deaths across different scenarios.

## 2. Methods

### 2.1. Epidemiological data

In Japan, anyone who visited an outpatient department with suspected COVID-19 received reverse transcriptase-polymerase chain reaction testing, and all diagnosed cases had to be notified to the national surveillance system. Two types of data were used in this study: training data and simulation data. The training data were the empirical data used to reconstruct the transmission dynamics of COVID-19 in Tokyo. The simulation data, again empirically observed, were used for the numerical simulations and to evaluate the model performance by comparing it with modeled epidemiological outcomes. To ensure that the training data fully reflected the expected transmission dynamics of the SARS-CoV-2 Alpha variant, these data included information about COVID-19 incidence in Osaka prefecture from 5 March to 9 April 2021, when more than 70 % of screened samples were confirmed as the Alpha variant and the remaining 30% were from the wild-type strain, i.e., the original SARS-CoV-2 from Wuhan, China (Ministry of Health Labor and Welfare, 2021c). The incidence data during the period with the Delta variant were not included in the training data because this study intended to offer scenario-based projections in advance of the Tokyo Olympic Games, when the Delta variant had yet to outcompete other SARS-CoV-2 variants in Japan (Ministry of Health Labor and Welfare, 2021d). The benefit of using data from Osaka is that no large-scale PHSMs (e.g., national- and prefectural-level lockdown) were implemented during that period in that region, enabling us to statistically infer the spread of the Alpha variant during the Olympic Games, when there may be less adherence to physical distancing guidelines. On the other hand, the Alpha variant became dominant in Tokyo in late April (Ministry of Health Labor and Welfare, 2021e) after the implementation of a quasi-state of emergency (9 April) which could adulterate the transmission dynamics. The simulation data included confirmed COVID-19 cases reported in Tokyo Metropolis from 15 March to 15 August 2021, including the number of severe cases with intubation. Both datasets (i.e., training and simulation data) were retrieved from publicly available reports posted on the websites of the Ministry of Health, Labor and Welfare and Tokyo Metropolitan Government (Ministry of Health Labor and Welfare, 2021b; Tokyo Metropolitan Government, 2021a). In total, 11,127 cases were included in the training data, and 163,723 cases in the simulation data. Cases were aggregated into four age groups: individuals aged 0–19 years, 20–39 years, 40–59 years, and 60 years and older.

### 2.2. Model formulation and parameterization

#### 2.2.1. Reconstruction of the next-generation matrix

We devised a discrete-time deterministic compartmental model structured by age group, including the SARS-CoV-2 transmissions between and within the domestic population and international participants, to estimate unknown parameters and offer a baseline model (Fig. S1). We fitted the baseline model to age-stratified COVID-19 incidence from the training data to estimate the relative susceptibility to COVID-19 infection in each of the four age groups, given the rescaled contact pattern between age groups in Japan (Munasinghe et al., 2019; Röst et al., 2020) (Fig. S2). The 95% confidence intervals (CIs) of the estimates were derived using the parametric bootstrap method with 10, 000 times resampling exercise. Using this metric, we then reconstructed the age-stratified next-generation matrix, governing the transmission dynamics of COVID-19 between age groups in Japan, and derived the reproduction number ($R$) of the Alpha variant from its leading eigenvalue. We then applied the reconstructed next-generation matrix to the Tokyo setting, imposing an assumption that the contact pattern would be the same in the two metropolitan prefectures (i.e., Tokyo and Osaka). Full details of the parameter choice and model description can be found in Table S1 and Supplementary materials Section *2*.

#### 2.2.2. Scenarios for the possible transmission dynamics of COVID-19

We then performed numerical simulations to assess (i) the number of newly reported COVID-19 cases; (ii) the prevalence of severe cases needing intensive care admission; (iii) the prevalence of severe cases with intubation; and (iv) the cumulative number of COVID-19 deaths. We used the baseline model, incorporating the planned vaccine roll-out strategy and Tokyo Olympic Games, and varying the levels and duration of possible countermeasures during the Olympic period (i.e., 16 July–15 August 2021, including 1 week before and after the Games themselves). To model the possible transmission dynamics of COVID-19 in Tokyo during the Olympic Games, we considered five different scenarios (Scenarios 1–5) using the 7-day stepwise $R_t$ within the domestic population (Fig. S4). Given that the fourth SoE was declared while the Delta variant still accounted for less than 40 % of detected cases in Tokyo (Ministry of Health Labor and Welfare, 2021f), the transmission dynamics during the Olympic Games period would be affected by both the rapid spread of the Delta variant and the stringent PHSMs. Five scenarios of time-varying $R_t$ were therefore introduced in response to both factors (i.e., the higher transmissibility of the Delta variant and effects of the fourth SoE). The $R_t$ among international Games participants was assumed to be constant over time, and was set at 1.20 (i.e., 85 % of the $R$). The baseline $R_t$ within the domestic population was set at 1.28 (i.e., 90 % of the $R$) based on the estimated $R_t$ using actual case counts (Ministry of Health Labor and Welfare, 2021g). It was assumed to increase to 1.70 (i.e., 120 % of the $R$) from 19 to 25 July 2021 because of increased mobility during the period linked to a 4-day holiday in Japan. From 26 July 2021, a gradual increase in the $R_t$ was introduced into Scenario 1 to reflect the possibility that the fourth SoE might be insufficient to bring the epidemic under control because of the elevated mobility and rapid spread of the Delta variant. Scenario 2 used a constant $R_t$ of the baseline value (1.28). In Scenarios 3–5, we modeled the $R_t$ following the trend of the “de facto population” in seven main nightlife districts of Tokyo from 10 pm to midnight during the third SoE (i.e., the population size measured by the number of mobile phone users in a particular geographic area) (Ministry of Health Labor and Welfare, 2021h). These data provide a very good proxy for human mobility in high-risk settings for SARS-CoV-2 transmissions (having close contact in crowded and closed spaces, e.g., drinking in bars and restaurants). Before large-scale community-level transmission was observed in late August 2021, it was suggested that individuals associated with high-risk settings had primarily driven the COVID-19 epidemic in Japan (Jung et al., 2021). In addition, the effectiveness of the third and fourth SoEs were considered unlikely to be identical because of changes in risk awareness, moreover, such changes would not be simply proportional to time, but also be influenced by psychological factors (Schneider et al., 2021). We therefore introduced variations in the degree of changes in the $R_t$ are introduced; smaller changes in the $R_t$ were assumed in Scenario 3 and larger changes in Scenario 5. To take into account rigid restrictions on physical contact set by the IOC (International Olympic Committee, 2021), we also modeled limited inter-group transmission (i.e., SARS-CoV-2 transmission between the domestic population and international participants) using a high assortativity coefficient $\theta$ (set at 0.99, where 1 indicates a perfect assortative mixing between groups) and relative population size of each group in each scenario (Nishiura et al., 2011) (see Supplementary materials Section 4). After the Olympic period, we assumed that an additional SoE ($R_t = 0.9$) would be implemented if the prevalence of severe COVID-19 cases in Tokyo was higher than 50% of the existing intensive care unit (ICU) capacity in the city (187 cases), and would be maintained until cases reached 20% of ICU capacity (75 cases). This fits the subjectively determined governmental definition of “Alert level 3 and 4″ in Japan (Cabinet Relations Office, 2020) (Tokyo Metropolitan Government, 2021b). Lastly, once the prevalence of severe cases decreased to Alert level 3, the $R_t$ was set to the same value as $R$, because we anticipated that the minimum level of PHSMs would be implemented by political decision. This would be justified by the lighter burden of disease on healthcare settings along with increasing vaccination coverage in the population.

### 2.2.3. *Inclusion of COVID-19 vaccination*

The COVID-19 vaccination program was already underway at the start of the simulation (1 April 2021). Vaccines were modeled to be allocated only to the highest priority group (i.e., individuals aged 60 years and over), and we assumed that 80 % of this group would be vaccinated by 31 August 2021, in line with the planned vaccine roll-out in Japan (Cabinet Relations Office, 2021d). After that, we assumed that vaccination would be offered equally to all individuals aged 20 years and over. For simplicity and because of the very short time lag from vaccination to the Olympic Games, we assumed that lifelong immunity would be instantly acquired through either vaccination or natural infection.

### 2.2.4. *Numerical simulations assessing the possible impact of countermeasures*

Using the proposed model, we quantitatively assessed the impact of four different countermeasures during the Olympic Games on the transmission dynamics of COVID-19 in Tokyo. These were as follows: (i) not hosting the Olympics; (ii) not having spectators; (iii) increasing the maximum ICU capacity in Tokyo; and (iv) imposing a stringent SoE ($R_t = 0.7$) from the end of Olympic Games (i.e., 8 August 2021). First, to model the impact of hosting the Olympic Games on the transmission dynamics of COVID-19 in Tokyo, we simulated the model with and without compartments related to international Games participants. Second, to evaluate the impact of having spectators, the opportunity for inter-group transmissions ($\theta$) was varied between 0.95 and 0.99. Third, we also varied the maximum ICU capacity in Tokyo, to determine the required duration of the additional SoE after the Olympics. Lastly, we evaluated the potential impact and optimal duration of a stringent SoE from the end of the Olympic Games to keep the number of severe cases below the existing ICU capacity in Tokyo (373 cases). We also carried out sensitivity analyses, assessing the peak prevalence of severe cases and the cumulative number of deaths by varying the $R_t$ among visitors (ranging from 0.9 to 1.2) and the maximum ICU capacity in Tokyo (373–1000 units). All analyses used R statistical software and more details of the methodology can be found in the Supplementary materials.

## 2.3. *Ethical considerations*

This study only analyzed publicly available data. The datasets used in our study were de-identified and fully anonymized in advance, and the analysis of publicly available data without identity information does not require ethical approval.

## 3. Results

Table S1 shows the estimated age-stratified relative susceptibility, fitting the baseline model to the age-stratified incidence data in Osaka. The highest susceptibility was seen in individuals aged 20–39 years, followed by those aged 40–59 years old. Fig. S3 shows that the modeled COVID-19 incidence based on the estimates was mostly in line with the overall trend of observed incidence in all age groups. This implies that our estimated parameters properly captured the age-stratified transmission dynamics of COVID-19 in Japan. Table 1 shows the next-generation matrix reconstructed using the estimated age-stratified relative susceptibility and age-stratified contact pattern. On the basis of the reconstructed next-generation matrix, the $R$ of the Alpha variant under the self-restrained PHSMs was estimated at 1.42 (95 % CI: 1.41–1.42).

Rows show the age of exposed individuals, and columns show the age of the primary case. Each value describes the transmission rates within and between groups (0–19, 20–39, 40–59, and 60 years and over [60 +]). The reproduction number ($R$) was derived from the leading

**Table 1**
Reconstructed age-dependent next-generation matrix of the Alpha SARS-CoV-2 variant in Japan.

| | 0–19 | 20–39 | 40–59 | 60 + |
|---|---|---|---|---|
| 0–19 | 0.69<br>(0.68–0.72) | 0.37<br>(0.36–0.38) | 0.34<br>(0.32–0.34) | 0.11<br>(0.10–0.11) |
| 20–39 | 0.11<br>(0.11–0.12) | 0.87<br>(0.86–0.89) | 0.38<br>(0.36–0.38) | 0.22<br>(0.21–0.22) |
| 40–59 | 0.14<br>(0.14–0.15) | 0.52<br>(0.51–0.52) | 0.51<br>(0.49–0.52) | 0.28<br>(0.27–0.28) |
| 60 + | 0.04<br>(0.04–0.04) | 0.24<br>(0.24–0.24) | 0.22<br>(0.22–0.23) | 0.50<br>(0.48–0.51) |

$\mathscr{R} = 1.42$ (1.41–1.42)

eigenvalue of the next-generation matrix. The table shows the median, and 95 % confidence intervals obtained from the parametric bootstrap method are shown in parentheses.

Fig. 1 shows the impact of hosting the Olympic Games on the transmission dynamics in Tokyo using the model with and without accounting for the involvement of Olympic participants. In both situations, as the $R_t$ within the domestic population increased (following each scenario), the incidence substantially escalated. The prevalence of severe cases exceeded the existing ICU capacity in Tokyo during the Olympic period, but there was no resurgence of severe cases after lifting the additional SoE (i.e., when the prevalence of severe cases decreased to 20 % of the ICU capacity in the post-Olympic period) in any scenario. However, the model without SARS-CoV-2 transmissions facilitated by international participants showed no particular reduction in the number of reported cases and prevalence of severe cases (Fig. 1E–H). This suggests that hosting the Olympic Games in Tokyo would have a limited impact on COVID-19 transmission dynamics in the population, provided that $R_t$ was identical among the domestic population with and without the Games.

Projected transmissions of SARS-CoV-2 in Tokyo using the model with (A–D) and without (E–H) considering transmission facilitated by international Olympic Games participants. Four epidemiological outcomes are shown: (i) number of newly infected cases; (ii) prevalence of severe cases with intubation; (iii) prevalence of severe cases in intensive care units (ICUs); and (iv) the cumulative number of deaths from the start of the simulation (1 April 2021). Yellow bars show the empirically observed number of newly reported cases (A, E) and prevalence of severe cases with intubation (B, F) from the start of the simulations. Colored lines and shaded areas show the projected transmission dynamics of COVID-19 by scenario (1−5) and the 95 % confidence intervals derived using the parametric bootstrap method. Purple shaded areas show the state of emergency, and the pink shaded area is the time period for the Tokyo Olympic Games. The black dashed lines show the number of existing intensive care unit (ICU) beds in Tokyo. The red and light gray dashed lines are 50 % and 20 % of the existing ICU capacity, which correspond to the governmental definition of "Alert level 3 and 4″ in Japan.

The quantified impact of having spectators at the Olympic Games on the expected incidence and prevalence of severe cases with intubation in each scenario is shown in Fig. 2. Projections show that increases in inter-group transmission could lead to a rapid surge in both incidence (Fig. 2A–C) and prevalence of severe cases (Fig. 2D–F). The impact of spectators was also greater in scenarios with a higher $R_t$ within the domestic population because the degree of inter-group transmissions is governed by both assortativity coefficient ($\theta$), and the $R_t$ within each group (see Supplementary materials Sections 2–1). When there is active inter-group transmission ($\theta = 0.95$), the scenario with a gradual increase in the transmissibility (Scenario 1) showed a substantial increase in the number of newly reported cases, exceeding 10,000 cases by the end of the Olympic Games. As was the case for Fig. 1, Fig. 2 shows that the incidence decreased after the Olympic Games because we assumed that an additional SoE would then be implemented because of excess ICU admissions.

Panels A–F show the projected impact of spectators at the Olympic Games on the transmission of COVID-19 in Tokyo, varying the level of inter-group transmission ($\theta$; range 0.95–0.99). Two epidemiological outcomes are shown: the number of newly infected cases and prevalence of severe cases with intubation. Yellow bars show the empirically observed number of newly reported cases (A–C) and prevalence of severe cases with intubation (D–F) from the start of the simulations. Colored lines and shaded areas show the projected transmission dynamics of COVID-19 by scenario (i.e., five different trends for transmission within the domestic population) and 95 % confidence intervals derived using the parametric bootstrap method. Purple shaded areas show the state of emergency (SoE), and the pink shaded area is the time period for the Tokyo Olympic Games. Panels G–I show comparisons of epidemiological outcomes by different levels of inter-group transmission and different scenarios using the median value of projected results: peak prevalence of severe cases in intensive care units (ICUs) (G), required duration of the SoE after the Olympic Games (i.e., from the end day of Olympic Games to the date when the prevalence of severe cases decrease to 20 % of the existing ICU capacity in Tokyo) (H), and cumulative number of deaths from the start of the simulation (1 April 2021) (I).

Panels A–F show projected transmission dynamics of COVID-19 in Tokyo, varying the intensive care unit (ICU) capacity (ranging from the current level, 373, to 1000 units). Two epidemiological outcomes are shown: the number of newly infected cases and prevalence of severe cases with intubation. Yellow bars represent the empirically observed number of newly reported cases (A–D) and prevalence of severe cases with intubation (E–H) from the start of the simulations. Colored lines and shaded areas show the projected transmission dynamics of COVID-19 by scenario (i.e., five different trends in transmission within the domestic population) and 95 % confidence intervals derived using the parametric bootstrap method. Purple shaded areas show the state of emergency (SoE), and the pink shaded area the Tokyo Olympic Games. Panels I–K show comparisons of epidemiological outcomes by different

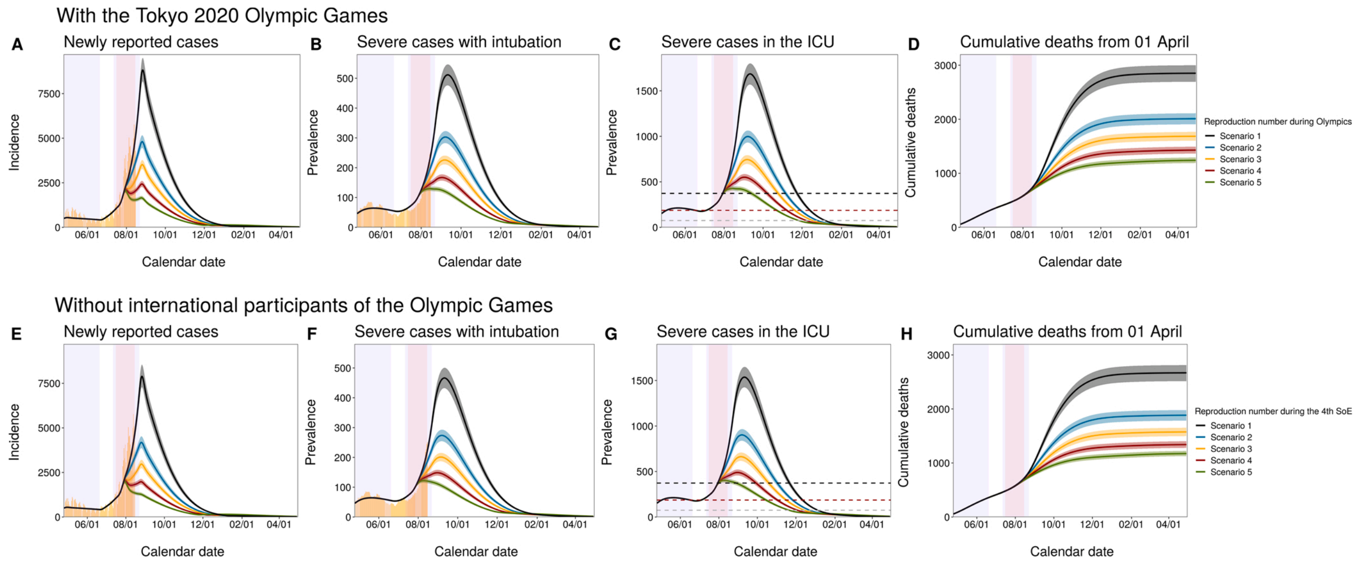

**Fig. 1.** Projected impact of international Olympic Games participants on the transmission dynamics of COVID-19 in Tokyo.

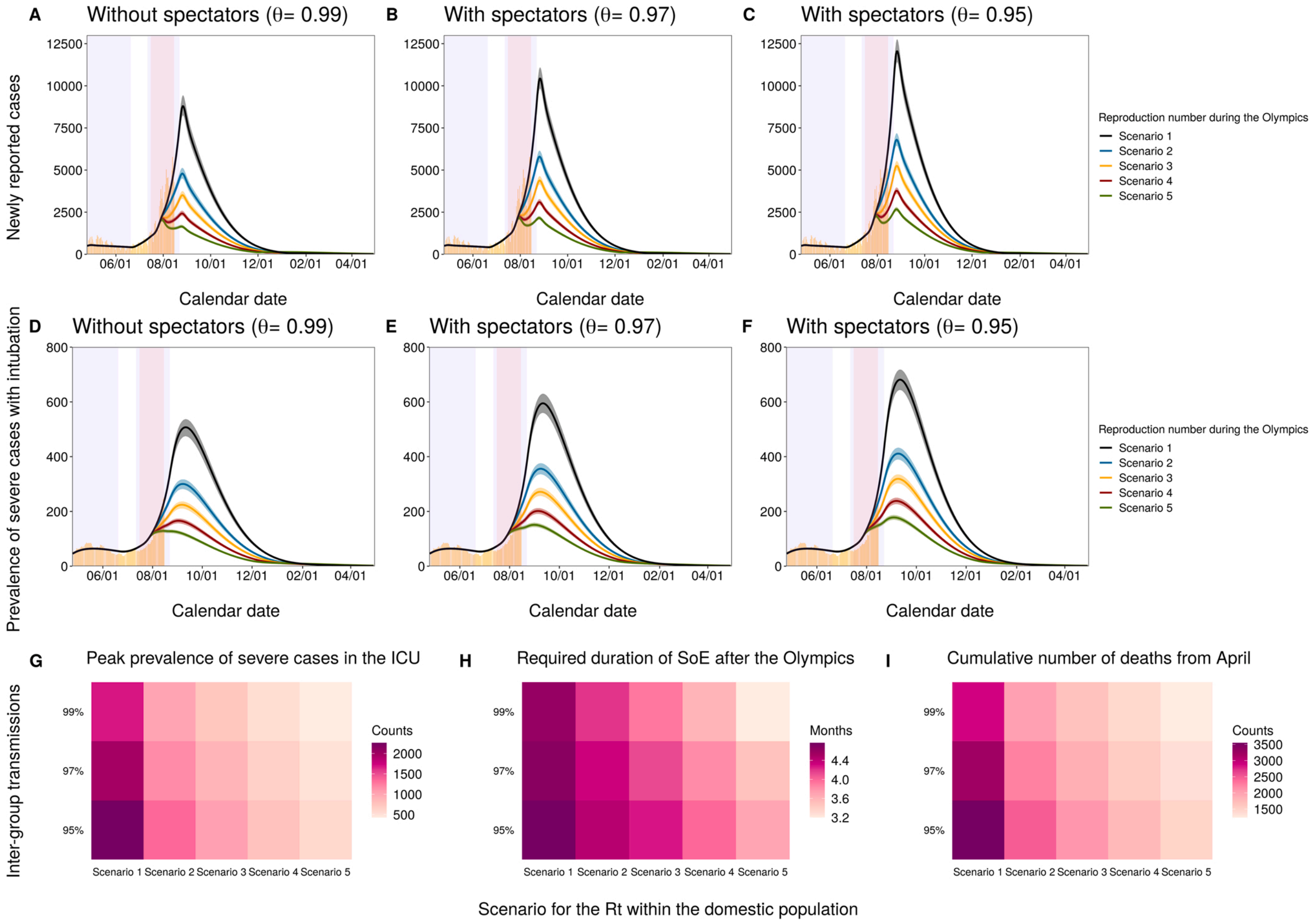

**Fig. 2.** Projected impact of spectators at the Tokyo Olympic Games on the transmission dynamics of COVID-19 in Tokyo.

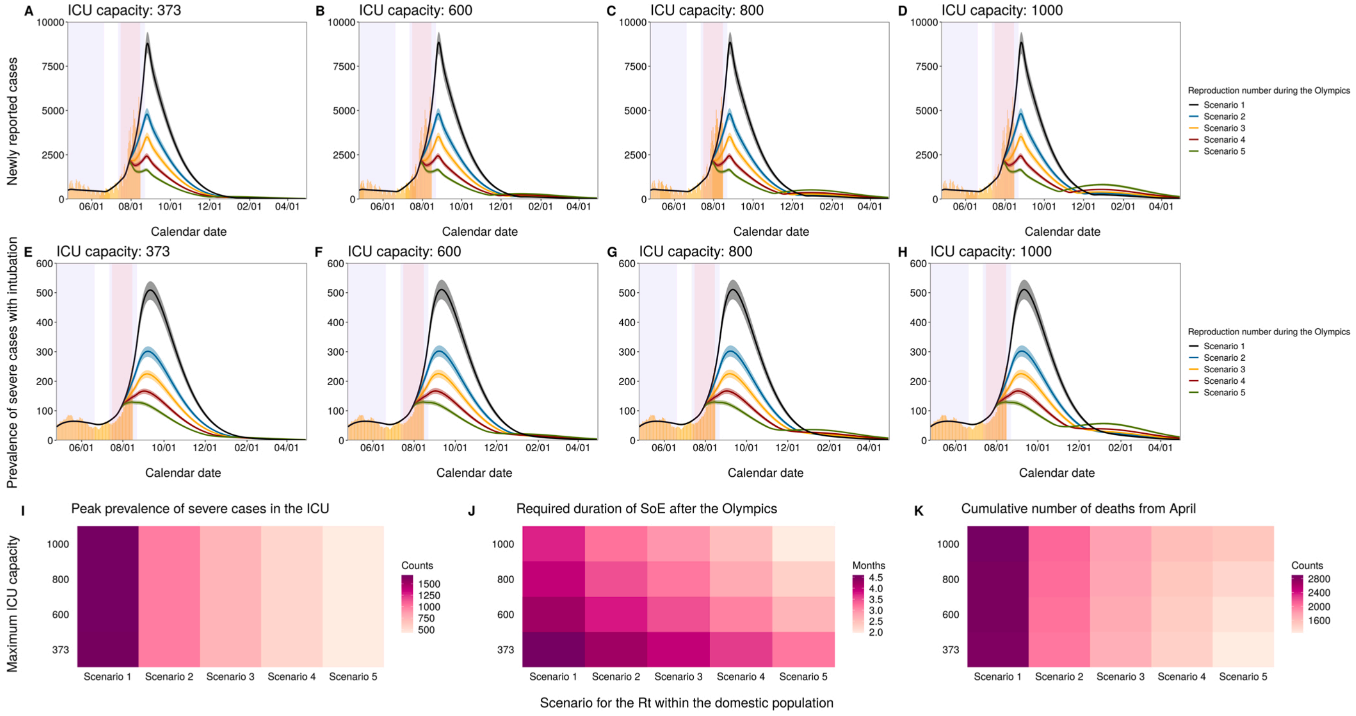

**Fig. 3.** Projected impact of expanding intensive care unit capacity on the transmission dynamics of COVID-19 in Tokyo.

levels of ICU capacity and different scenarios using the median value of projected results: (I) Peak prevalence of severe cases in the ICU, (J) Required duration of the SoE after the Olympic Games (i.e., from the end day of Olympic Games to the date when the prevalence of severe cases decreases to 20 % of the existing ICU capacity in Tokyo), and (K) Cumulative number of deaths from the start of the simulation (1 April 2021).

Fig. 3 shows the possible impact of extending the maximum ICU capacity in Tokyo on the transmission dynamics. Increasing capacity to 1000 units could lower the required duration of SoE beyond the Olympic period to less than 3 months. However, the peak prevalence of severe cases needing intensive care still exceeded the expanded capacity in Scenario 1. In Fig. 4, the optimal duration of stringent SoE ($R_t = 0.7$) required to bring the prevalence of severe cases under the existing ICU capacity in Tokyo was assessed across different scenarios. Our model shows that imposing a stringent SoE for more than 8 weeks from the end of the Olympic Games (8 Aug 2021) could minimize the required duration of SoE in all scenarios (Fig. 4J–K). However, the overall transmission dynamics of COVID-19 in Tokyo (i.e., the peak number of severe cases in ICU and the cumulative number of deaths) remained consistent over different durations of SoE. Fig. S5 shows that the sensitivity analyses assessing the peak number of severe cases and cumulative deaths with varied $R_t$ among visitors and maximum ICU capacity had similar results.

Panels A–F show projected transmission dynamics of COVID-19 in Tokyo by varying the duration of a stringent state of emergency (SoE) ($R_t = 0.7$) from 2 to 8 weeks. Two epidemiological outcomes were compared: the number of newly infected cases and prevalence of severe cases with intubation. In all simulations, the stringent SoE was assumed to be implemented from the end of the Olympic Games (8 August 2021). Yellow bars show the empirically observed number of newly reported cases (A–D) and prevalence of severe cases with intubation (E–H) from the start of the simulations. Colored lines and shaded areas show the projected transmission dynamics of COVID-19 by scenario (i.e., five different trends in transmission within the domestic population) and 95 % confidence intervals derived using the parametric bootstrap method. Purple shaded areas show the SoE, and the pink shaded area the Tokyo Olympic Games. Panels I–K show comparisons of epidemiological outcomes by duration of the stringent SoE, and different scenarios using the median value of projected results: (I) Peak prevalence of severe cases in intensive care units (ICUs), (J) Required duration of the SoE after the Olympic Games (i.e., from the start day of the stringent SoE to the date when the prevalence of severe cases decreases to 20 % of the existing ICU capacity in Tokyo), and (K) Cumulative number of deaths from the start of the simulation (1 April 2021).

Fig. S6 shows the averted risk estimate of epidemiological outcomes as a result of possible COVID-19 response strategies (i.e., canceling spectators, expanding the ICU capacity, and imposing the stringent SoE) during the Olympic Games period. Fig. S7 shows the comparison between the projected and observed incidence and prevalence of severe cases with intubation by age group in Tokyo. Given the estimated parameters, the projected epidemiological outcomes were well aligned with the overall trend of empirically obtained values from the time series of COVID-19 data in Tokyo. This level of model performance implies that the age-structured dynamics of SARS-CoV-2 transmissions were well reconstructed in our study, even though such epidemiological trends might be also driven by other factors that are not considered in the proposed model (e.g., different ascertainment rates by age group).

## 4. Discussion

This study used a model-informed approach to quantitatively evaluate the effects of possible COVID-19 response strategies during the Tokyo Olympics, taking into account different levels of countermeasures and possible transmission dynamics of COVID-19 in Tokyo. It used age-stratified incidence data representing the transmission dynamics of the Alpha variant under voluntary restrictions. The highest relative susceptibility to COVID-19 was seen in individuals aged 20–39 years, implying that people in this age group acted as the major transmitting group in Japan. There were no major differences between holding and not holding the Olympic Games under the assumed identical $R_t$. However, banning spectators had a substantial impact on reducing the incidence and hospitalizations in Tokyo.

One of the model-based findings suggested that controlling the SARS-

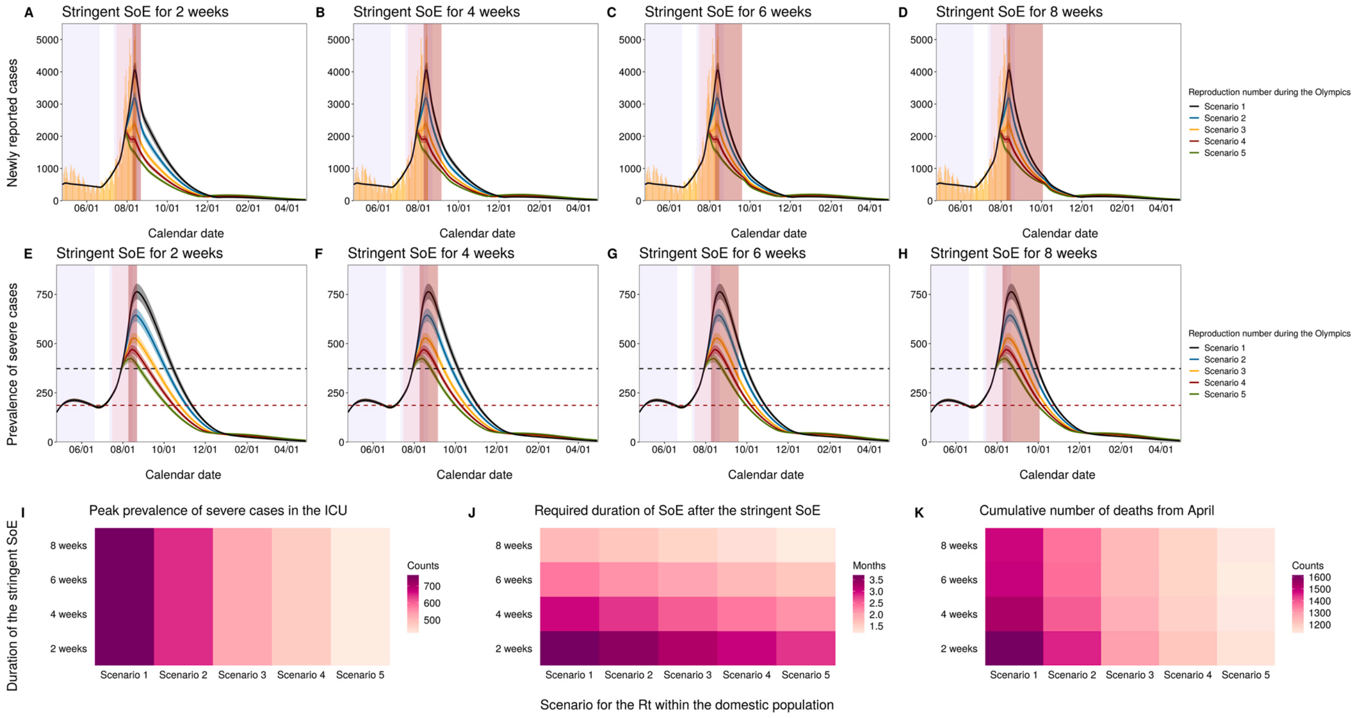

**Fig. 4.** Projected impact of imposing a stringent state of emergency after the Tokyo Olympic Games on the transmission dynamics of COVID-19 in Tokyo.

CoV-2 transmissions facilitated by international Olympic Games participants may not lead to a substantial reduction in the COVID-19 incidence. This result is mainly driven by the assumed high assortative mixing between the domestic population and international participants ($\theta = 0.99$), as well as the high proportion of vaccinated individuals among Games participants (set as 80 %), which are both empirically supported. The estimated vaccination coverage among athletes was above 80 % (Reuters, 2021) and they were also subjected to strict testing requirements and restrictions on physical interaction with the general population (e.g., not allowed to take public transport and could only leave their accommodation to go to official Olympic venues) during the Olympic Games (International Olympic Committee, 2021). As a result, out of all the Olympic-related COVID-19 cases, including all staff and volunteers, there were only 147 cases (32 %) among non-Tokyo residents, who were most likely to contract the disease in Olympic venues (National Institute of Infectious Diseases, 2021). We were unable to identify cases who tested positive on arrival among those 147 cases, and transmissions among international participants during the Olympic Games might therefore have been even lower than this. The modeled SARS-CoV-2 transmissions among international participants (353 cases) were slightly higher than the reported case counts, which is probably because some athletes promptly returned to their own countries after finishing their games; this was not included in our model settings (Filks, 2021).

Our model-informed approach showed that minimizing the intergroup transmissions by banning spectators, who could act as mediators between the domestic population and Olympic Games participants, could play a crucial role in minimizing the SARS-CoV-2 transmissions in Tokyo. During the Tokyo Olympic Games, the vaccination coverage was insufficient to achieve herd immunity even temporarily (i.e., not enough to reach the required proportion of immune individuals in the population to enable the spread of the disease to decline, given the transmissibility of SARS-CoV-2 under PHSMs and vaccine roll-out) (Leung et al., 2021). Despite a substantial increase in COVID-19 incidence during the 4-day holiday in July 2021, as of 21 July (i.e., the date of the first Tokyo Olympic event), approximately 1 % and 37 % of the total Tokyo population were reported to be infected and vaccinated with a single dose (Tokyo Metropolitan Government, 2021a). When the transmissibility of SARS-CoV-2 among the domestic population increased under the proposed scenarios, activated inter-group transmissions via spectators showed a remarkable impact on the transmission dynamics of COVID-19 in Tokyo. Under these scenarios, the prevalence of severe cases exceeded the current ICU capacity. As shown in the rapid surge of COVID-19 cases in the United Kingdom and the United States in July 2021 (del Rio et al., 2021), the increased transmissibility of the Delta variant can lead to a greater burden than previous waves. It could even be accelerated if a decrease in adherence to physical distancing, low vaccine coverage, and decrease in detection rate with high incidence were combined during the Olympic period (Borchering et al., 2021; Truelove et al., 2021; Wu et al., 2020). Thus, the rapid spread of the Delta variant and likely increased human mobility in Tokyo during the Olympic period meant that it was crucial to control inter-group transmissions to minimize the prevalence of severe COVID-19 cases.

With the anticipated increase in COVID-19 incidence, our model showed that expanding the ICU capacity in Tokyo effectively decreased the required duration of the additional SoE after the Olympic period, endorsing the Tokyo prefectural government's planned response strategy (Tokyo Metropolitan Government, 2021b). The current ICU capacity in Tokyo required stringent social distancing measures to be imposed for more than 8 weeks from the end of the Tokyo Olympic Games to suppress the prevalence of severe cases. It is hard to maintain rigid restrictions on physical contact under the SoE for an extended time in Japan because of their considerable economic, social, and psychological impact. Adherence to physical distancing measures also tends to diminish gradually in practice (Crane et al., 2021). Both countermeasures (i.e., the expansion of ICU capacity and implementation of a stringent SoE but for a relatively short period) can be deemed an effective response strategy for minimizing socioeconomic damage, but bringing COVID-19 cases under control. Our model also shows that the cumulative number of deaths was not affected by ICU capacity. Notably, however, our model did not consider excess mortality, which might be observed when hospital demand exceeds available capacity (Keeling et al., 2021; Martin et al., 2021). Our simulations might therefore underestimate the achievable contribution of expanded ICU capacity to the reduction in the cumulative number of COVID-19 deaths.

This study also had some other limitations. First, it did not fully consider possible changes in the transmission dynamics of the domestic population without the Olympic Games. This scenario was partially assessed by comparing models with and without incorporating transmissions facilitated by international participants. However, if the cancellation of the Olympic Games caused a significant drop in SARS-CoV-2 transmissions among the domestic population (e.g., because of increased risk awareness among Tokyo residents), the projected impact of hosting the Tokyo Olympic Games would be considerably underestimated. Second, detailed characteristics of vaccines (e.g., vaccine effectiveness against hospitalization or waning of vaccinal immunity) were not fully considered in the model. Our model might therefore overestimate the prevalence of severe cases and the cumulative number of deaths because of higher vaccine effectiveness against hospitalization than infection (Tregoning et al., 2021). However, given the small number of vaccinated individuals in July, the proposed model was able to evaluate the overall impact of possible response strategies. Third, we explicitly accounted for the age-dependent risk of severity and fatality, but the risk of severe illness or death as a result of other factors (e.g., comorbidities) was not fully considered. Fourth, the contact patterns between residents and international participants could vary, but the same next-generation matrix was applied to both groups. However, these differences would have very little impact on our projections because the majority of international participants (90%) were assumed to be in two age groups (those aged 20–39 and 40–59 years) (The Guardian, 2012), and to have high vaccination coverage (80%). Lastly, only the prevalence of severe COVID-19 cases with intubation has been reported in publicly available reports from the Tokyo metropolitan government. The age-specific risk of severity among all confirmed cases therefore drew on the empirically observed value in Osaka prefecture (Ministry of Health Labor and Welfare, 2021e). Our projections might therefore under- or over-estimate the prevalence of severe cases. However, given the estimated proportion of severe cases with intubation among all severe cases (see Supplementary Materials Sections 2–1), the projected prevalence of severe cases with intubation was well aligned with the overall trend of empirical reported values from the Tokyo metropolitan government.

## 5. Conclusions

This study suggested that measures to control SARS-CoV-2 transmission among the domestic population (i.e., banning spectators and imposing a stringent state of emergency lasting more than 8 weeks) during the Tokyo Olympic Games would be essential to bring the prevalence of severe COVID-19 cases within the limits of existing intensive care unit capacity in Tokyo, especially with the rapid spread of new SARS-CoV-2 variants. Our model-informed approach provided quantitative guidance for a suitable COVID-19 response strategy that allowed the Olympic Games to be hosted but minimized the burden of disease in Tokyo.

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## CRediT authorship contribution statement

**Sung-mok Jung**: Conceptualization, Design, Formal analysis, Original draft preparation. **Katsuma Hayashi**: Data curation and Reviewing. **Taishi Kayano**: Data curation and Reviewing. **Hiroshi Nishiura**: Conceptualization, Reviewing, and Editing.

## 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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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.epidem.2022.100618.

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