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Research article

Not all fun and games: Potential incidence of SARS-CoV-2 infections during the Tokyo 2020 Olympic Games

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Abstract: The Tokyo 2020 Olympic and Paralympic Games represent the most diverse international mass gathering event held since the start of the coronavirus disease 2019 (COVID-19) pandemic. Postponed to summer 2021, the rescheduled Games were set to be held amidst what would become the highest-ever levels of COVID-19 transmission in the host city of Tokyo. At the same time, the Delta variant of concern was gaining traction as the dominant viral strain and Japan had yet to exceed fifteen percent of its population fully vaccinated against COVID-19. To quantify the potential number of secondary cases that might arise during the Olympic Games, we performed a scenario analysis using a multitype branching process model. We considered the different contributions to transmission of Games accredited individuals, the general Tokyo population, and domestic spectators. In doing so, we demonstrate how transmission might evolve in these different groups over time, cautioning against any loosening of infection prevention protocols and supporting the decision to ban all spectators. If prevention measures were well observed, we estimated that the number of new cases among Games accredited individuals would approach zero by the end of the Games. However, if transmission was not controlled our model indicated hundreds of Games accredited individuals would become infected and daily incidence in Tokyo would reach upwards of 4,000 cases. Had domestic spectators been allowed (at 50% venue capacity), we estimated that over 250 spectators might have arrived infected to Tokyo venues, potentially generating more than 300 additional secondary infections while in Tokyo/at the Games. We also found the number of cases with infection directly attributable to hypothetical exposure during the Games was highly sensitive to the local epidemic dynamics. Therefore, reducing and maintaining transmission levels below epidemic levels using public health measures would be necessary to prevent cross-group transmission.

Keywords: SARS-CoV-2; Olympics; Branching process; Tokyo 2020; COVID-19

1. Introduction

Amidst the uncertainty surrounding the rapid worldwide spread of severe acute coronavirus disease 2 (SARS-CoV-2) in late March 2020, the International Olympic Committee (IOC) and Tokyo Organizing Committee (TOCOG) decided to postpone the Tokyo 2020 Olympic and Paralympic Games (OPG) for a year. At th time, the host country of Japan had not experienced the same dramatic level of exponential growth in cases that was seen in Europe and North America. However, there were persistent clusters of infection as well as many sporadic (unlinked) cases showcasing persistent domestic transmission. As well, international border control efforts were in place, with further entry restrictions to be implemented in April 2020 [1].

Although the relatively low levels of transmission in 2020 in Japan had initially given some hope that the epidemic would be contained before the rescheduled OPG, in 2021 the epidemic situation in Japan grew more serious. Beginning in April, many prefectures in Japan alternated between declaring states of emergency (SoEs) and quasi-SoEs. Previously, SoEs had been interspersed with periods of few or no restrictions. As spring turned into summer, transmission levels in the OPG host city Tokyo (also the national capital and most densely populated city in Japan) were on the rise. Despite domestic transmission surpassing 2020 levels and a slow vaccine rollout [2], the IOC and TOCOG firmly insisted the OPG would be held at the rescheduled time, sparking international debate [3] and a statement from Japanese infectious disease and medical experts that if the OPG were to go forward, risk should be reduced as much as possible [4].

In recognition of the rising spread of SARS-CoV-2 variants and an uncertain epidemic situation worldwide, the IOC and TOCOG made some changes to err on the side of preventing disease spread as the local epidemic situation failed to improve. In March 2021, TOCOG declared that the Olympic Games would be held with no international spectators, then in late June capped domestic spectatorship at 50% capacity (or maximum 10,000 spectators at the larger venues and 20,000 for the Olympic Stadium), before conceding in mid-July that no spectators at all would be the least risky option [4]. The decision for no spectators came on the heels of concerning transmission rates in Tokyo that led to the declaration of a fourth SoE for the prefecture. This SoE was scheduled to last for the duration of the Olympic Games (see Figure 1).

Despite deciding to allow no spectators and providing guidance on infection control restrictions for all persons directly involved in the Games in the form of "Playbooks" [5], it was expected that domestic transmission would continue, and perhaps be enhanced by increases in mobility and contact associated with the OPG. Foreign visitors would by necessity interact with domestic contractors, volunteers, and OPG personnel, who themselves would interact with one another and with the general Tokyo population. This likely increase in the movement and contact rates indicated the potential for increased domestic transmission—or at least lessening of the impact of the SoE on reducing transmission in Tokyo.

To explore transmission dynamics during the Olympic Games we performed a scenario analysis where we aimed to quantify the potential number of secondary cases that might arise during the Games through the application of a multitype branching process model. We considered the different contributions to transmission of individuals directly involved in the Games, domestic spectators, and the general Tokyo population. In doing so, we demonstrated how transmission might evolve in these different groups over time, cautioning against any loosening of infection prevention protocols and supporting the decision by the IOC and TOCOG to ban spectators. We further contextualized this *a priori* modeling with post-hoc reports from TOCOG on the actual numbers and details of cases reported to be associated with the Olympic Games.

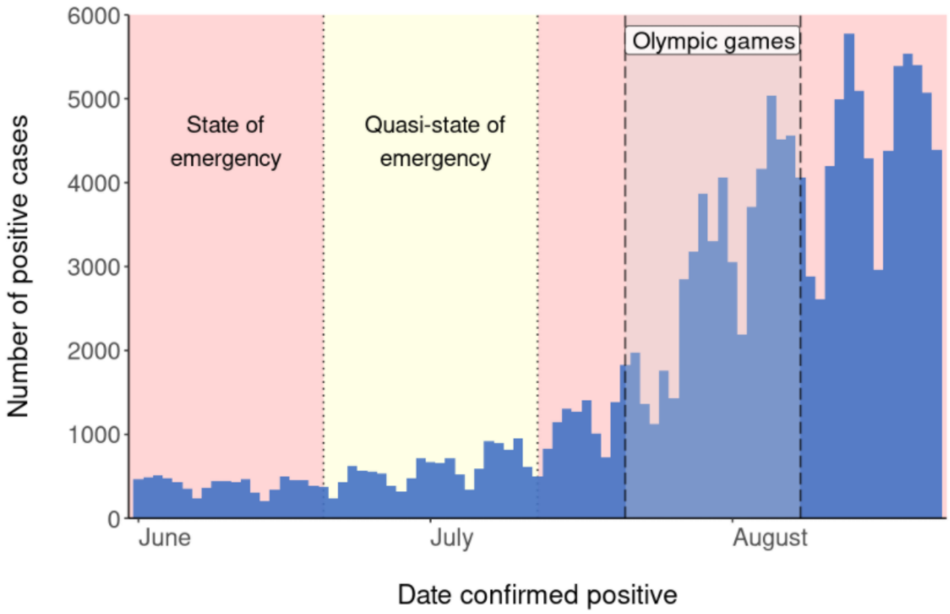

Figure 1. Epidemic curve of the COVID-19 pandemic in Tokyo before, during, and after the Olympic Games. Red shaded areas indicated states of emergency while yellow shaded areas show time periods when quasi-state of emergency measures were implemented.

2. Materials and methods

2.1. Model

We related the Olympics to six generations of infection, assuming a mean generation interval of 5 days [6,7]. We set generation zero to include the five days before the start of the main Olympic events (July 16–20), and the subsequent four generations encompassed the nineteen days of the Olympic Games plus one day after the closing ceremony (July 21–August 9). One additional generation following the Olympic Games was included to capture cases generated during the tail end of the Games. We chose to include a generation before the Olympic Games began because many individuals associated with the Games would have already arrived in Tokyo to prepare venues, equipment, or—in the case of the athletes—themselves.

The types in our multitype model consist of three groups: Games accredited individuals, the general Tokyo population, and potential domestic spectators. Games accredited individuals include all foreign and domestic persons accredited to be directly involved in the Games, and we obtained rough estimates of the numbers in these subgroups from reports in the news media [8]. We estimated the total number of spectators for each generation by considering the capacity of each venue in Tokyo (under the 50% capacity policy) and the number of days the venue would be in use. For the Tokyo population we considered the 2021 population estimate and given the short timescale ignored birth and death processes. The initial number of Tokyo cases (incidence of infection) we varied between 1,200, 1,500, and 1,800 per day, reflecting the variations seen in reported incidence leading up to the Games (Table 1). With these population sizes, we then estimated an initial number of infected cases for each generation to use in our branching process model. These initial numbers were roughly calculated based on prevalence, fraction vaccinated, vaccine effectiveness, number of recovered cases, and population sizes. The details of these calculations are presented in the Supplementary Materials.

Table 1. Parameters and values considered in the branching process models.

Parameter	Values considered
Initial prevalence of cases in Tokyo*	1200, 1500, 1800 per day
Baseline effective reproduction number†	0.7, 0.9, 1.2
Dispersion parameter‡	0.2, 0.6
Assortativity§	0.95, 0.99

* The 7-day moving average of cases reported in Tokyo during the week before the Olympics was ~1200 cases/day. The number of cases with onset during that time period was likely to be higher given the increasing trajectory of COVID-19 in Tokyo, so we also considered 1500 cases/day and 1800 cases/day as plausible starting values.

† As Tokyo would be under a state of emergency during the Games, our reference for the baseline effective reproduction number (R_b) was the average value of the effective reproduction number (R_e) reported during the middle of the third state of emergency (SoE) in Tokyo (week of May 17–24), which was around 0.9 [9]. From this value, we assume a scenario with more successful control would be represented by $R_b = 0.7$. We represented a scenario with less successful control and/or increased transmissibility due to dominance of the Delta variant using $R_b = 1.2$ as this was the estimated R_e during the week before the fourth SoE (June 29–July 5) began [10].

‡ There is no clear consensus on the value of the dispersion parameter used in COVID-19 negative binomial offspring distributions, but 0.2 is on the lower end and 0.6 is on the upper end of the spectrum of values reported in the literature [20–21].

§ We assume due to the strict infection prevention measures implemented at the Games, there would be very limited opportunity for homogenous mixing at the Games, and as such assumed values representing almost fully assortative mixing.

We constructed a next generation matrix (NGM) for the three groups assuming a baseline effective reproduction number (average number of secondary cases generated by a single primary case within the same group) R_b of 0.7, 0.9, or 1.2. $R_b = 0.9$ was chosen because it is the approximate value of the effective reproduction number in Tokyo during the previous (third) SoE [9], and $R_b = 0.7$ represents a scenario where the current SoE would have a greater impact on transmission dynamics in Tokyo compared to the previous SoE. We also interpreted it as reflecting the stringency of restrictions placed on Games accredited individuals. In contrast, $R_b = 1.2$ is the approximate value of the effective reproduction number reported in the week before the fourth SoE began [10]. It also reflects the possibility of that the fourth SoE would be insufficient to reduce R_b below the epidemic threshold value of 1 in the presence of increases in mobility related to the Olympics and dominance of the Delta variant in Japan. When this model was initially formulated, it was expected that the Delta variant would replace wild-type SARS-CoV-2 to become the dominant viral strain by the Olympics opening ceremony [11].

To account for the limited opportunity for inter-group transmission we considered an assortativity coefficient θ which takes a value from 0 to 1, with $\theta = 1$ indicating perfect assortative mixing [12]. In our model, we varied θ between 0.95 and 0.99 (i.e. very little cross-group mixing). We assumed a scenario where $R_{i,j}$ within the NGM (the average number of secondary cases in group i produced by a single infected case in group j) is then modeled as a simple mixture of the assortativity coefficient and the relative population proportion n_i for each of the three groups, where $n_i = \frac{N_i}{N_{total}}$, given a population size N_i for each group i.

$$R_{i,j} \propto \begin{cases} (1-\theta)n_i + \theta & for\, i = j \\ (1-\theta)n_i & i \neq j. \end{cases}, \tag{1}$$

When $i = j$ then $R_b = R_{i,j}$. We calculated the NGM separately for each generation due to the fluctuating population sizes of the Games accredited individuals and spectators groups. We then applied a multitype Bienaymé-Galton-Watson branching process model to obtain the number of secondary cases X generated by each infectious individual. A branching process model is a stochastic process that assumes an infinite supply of susceptible individuals. The probability that an individual of type $j = 1, \ldots, D$ gives birth to X_i individuals of type $i = 1, \ldots, D$ is given by an offspring distribution $p_j = \Pr(X = j)$, where D is the total number of types (here, represented as population categories) [13]. The first two types in our multitype branching process model are Games accredited individuals and the general Tokyo population. We add a third type when also considering domestic spectators. The probability generating function $h_j(s_1, \ldots, s_D)$ for $s \in [0,1]^D$ is written:

$$h_j(s_1, \ldots, s_D) = \sum_{x_1,\ldots,x_D=0} p_j(x_1 \ldots x_D) s_1^{x_1} \ldots s_D^{x_D}. \tag{2}$$

We assumed that the offspring distribution followed a negative binomial distribution with mean $R_{i,j}$ and dispersion parameter k [11], given as

$$h_j(s_1, \ldots, s_D) = \left(1 + \frac{R_{1j}}{k}(1 - s_1)\right)^{-k} \ldots \left(1 + \frac{R_{Dj}}{k}(1 - s_D)\right)^{-k} = g_{1j}(s_1) \ldots g_{Dj}(s_D). \tag{3}$$

Because spectators were only involved in Olympic dynamics for one generation, for each generation n we used only the initial number of cases Z_{n-1} for generating secondary infections. The total number of cases in each generation was therefore the number of secondary cases generated X_n plus the number of new initial cases introduced in that generation, Z_n. However, only Z_n was used to calculate the number of secondary cases X_{n+1}. We ran 10,000 simulations for each of the branching process scenarios using R version 4.1.0 [14].

2.1.1. Ethics approval of research

This study analyzed data that are publicly available, having previously been de-identified. The analysis of publicly available data without identity information did not require ethical approval.

3. Results

The initial number of cases by generation for the three different groups are shown in Table 2. We estimated there would be four cases of the ~42,000 people arriving from abroad who would escape detection at the airport and potentially contribute transmission dynamics during the analysis period. Among domestic Games affiliated individuals, we estimated 70–120 initial cases. The total number of spectators expected to attend the Games in Tokyo based on the 50% capacity guidelines was just over 2 million (Figure 2A) and based on recent prevalence of COVID-19 in Japan we estimated that the initial number of cases for the spectators group ranged from 48–89 per generation, depending on the number of venues and venue sizes where Games would be held during each time period.

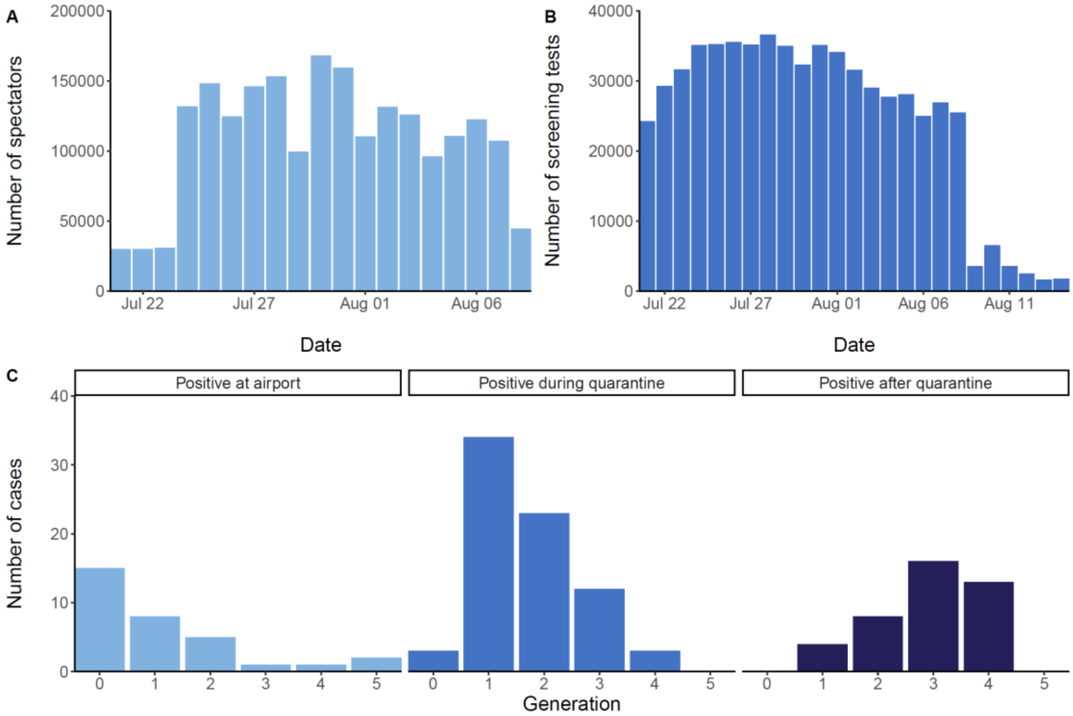

Figure 2. Possible number of domestic spectators by day in Tokyo, and number of Olympics screening tests held by day during the Olympic Games. A, possible number of spectators was calculated based on venue size, days in use for the Games, and capacity as reported on the official Tokyo 2020 website. B, the number of screening tests was reported on the official Tokyo 2020 website. C, number of foreign arrivals testing positive at the airport, during a 14-day quarantine period after arrival, or after a 14-day quarantine period by generation were reported on the official Tokyo 2020 website, with the former category and latter two categories shared as different datasets.

Table 2. Initial number of cases in each group by transmission generation. The number in parentheses represents the number of initial cases expected with a reduced volunteer workforce due to spectators being banned.

Start date	Generation	Tokyo incidence: 1200 cases/day		Tokyo incidence: 1500 cases/day		Tokyo incidence: 1800 cases/day		
		Games accredited individuals	Tokyo population	Games accredited individuals	Tokyo population	Games accredited individuals	Tokyo population	Tokyo spectators
16 July	0	36 (30)	6000	44 (37)	7500	52 (44)	9000	0
21 July	1	36 (30)	0	44 (37)	0	52 (44)	0	48
26 July	2	9 (8)	0	11 (10)	0	13 (11)	0	89
31 July	3	9 (8)	0	11 (10)	0	13 (11)	0	81
5 Aug	4	0	0	0	0	0	0	50
10 Aug	5	0	0	0	0	0	0	0

Our main results are shown in Figure 3. For the Games accredited individuals and general Tokyo population, when $R_b < 1$ the number of incident cases decreased with each generation. When $R_b > 1$ the number of incident cases increased with each generation. When the initial number of cases was its highest and $R_b = 1.2$, the number of newly infected cases averaged ~50 per day for Games accredited individuals and ~4,000 cases per day in the Tokyo population by the final generation for the scenario including spectators. In contrast, if $R_b < 1$ the number of cases would decline, reducing to fewer than ten newly infected cases per day in the final generation for Games accredited individuals, and reducing to <600 cases per day in the final generation for the Tokyo population. Table 3 shows the scenarios with the minimum and maximum number of new infections by group.

Similar to a previous study of the Hajj in 2014 [15], this study sought to contextualize analysis performed before a mass gathering event to the data reported following the event. To this end, we show reported cases among Games accredited individuals in Figure 3 alongside the estimated number of infections in each generation using our branching process model. Our estimated values most closely resembled the reported cases for the analysis period (grey bars in Figure 3) among Games accredited individuals when initial incidence in Tokyo was 1,500 cases per day and R_b was 0.7. Our estimated values most closely resembled cases in the Tokyo population (by date of onset) when initial incidence in Tokyo was 1,800 cases per day and R_b was 1.2. The reported number of cases is shown by reported or backprojected date of onset (for the general Tokyo population) and backprojected date of onset (for domestic Games accredited individuals) or date of report (for foreign Games individuals, most of whom would have been tested for SARS-CoV-2 daily and therefore likely been detected around time of onset). For the domestic spectators group, as secondary cases X_n generated by initial cases in the previous generation (Z_{n-1}) were subsequently removed from the next generation's transmission dynamics, the results do not resemble those of a classical branching process model.

Between-group infections also occurred, ranging between 3–268 for the entire Olympic period, depending on the selected values of R_b, k, θ, initial incidence in Tokyo, and whether spectators were included. The number of between-group infections increased with R_b and higher daily incidence in Tokyo. In the scenario including spectators, the largest number of between-group infections were between domestic spectators and the Tokyo population, as the two largest groups. No infections were estimated to occur between Games accredited individuals and the domestic spectators group, though had spectators been allowed the role of Games volunteers in interacting with spectators during the Games may have resulted in some between-group infections. A small number of infections were estimated to occur between the Games accredited individuals and domestic Tokyo population groups.

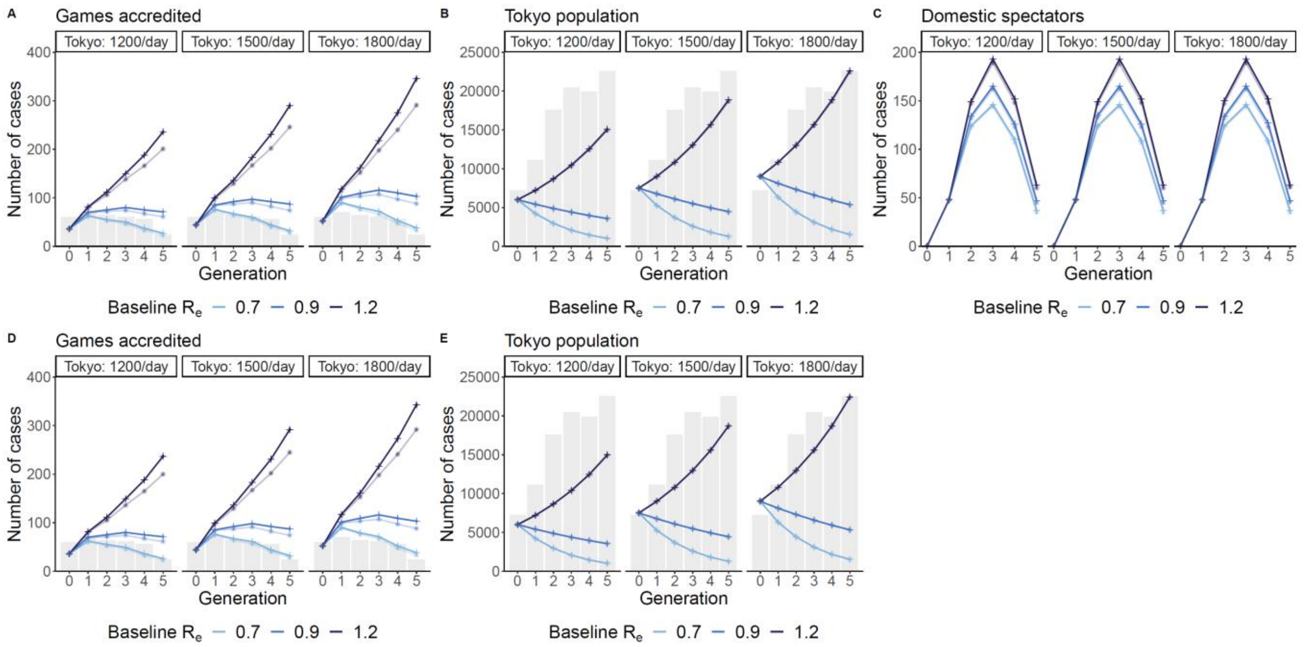

Figure 3. Number of cases by generation with varying baseline effective reproduction number (R_b) and incidence levels in Tokyo. Potential number of cases over six generations for a scenario including domestic spectators (A, Games accredited individuals, B, Tokyo population, and C, domestic spectators in Tokyo) as well as a scenario without domestic spectators (D, Games accredited individuals and E, Tokyo population) considering a varying initial incidence in Tokyo using data available before the Games started, for $k = 0.2$. The results for C are not that of a "classical" branching process model because generated cases are emigrated out after becoming infected. The bold lines show the values when assortativity tends towards slightly more random mixing, at $\theta = 0.95$, while the faded lines (when different enough from the solid lines to be visible) show results when mixing is more homogenous ($\theta = 0.99$). The grey bars show the actual number of cases as reported by the Tokyo Metropolitan Government and Tokyo 2020 by date of onset (as reported or backprojected), at which point they are presumed to be infectious and potentially contribution to transmission dynamics for that generation. As no dates of onset were reported for foreign Games accredited individuals and the reporting delay could not be calculated for backprojection, we assumed that date of report is approximate to date of onset. As many individuals in this group were tested daily and would have been detected around or before symptom onset, this simplifying assumption may provide a fairly accurate representation for this group.

Table 3. Minimum and maximum number of new infections generated in each group during July 16–August 9, 2021. R_b: baseline reproduction number. k: dispersion parameter. θ: assortativity parameter. "Tokyo incidence" refers to the assumed incidence per day in Tokyo during generation 0.

Group	R_b	k	θ	Tokyo incidence	Infections Initial	New	Total	Average per day
3-group scenario								
Games accredited	0.7	0.6	0.99	1200	90	161	251	9
Games accredited	1.2	0.2	0.95	1800	130	1041	1171	53
Tokyo population	0.7	0.6	0.99	1200	6000	11653	17653	583
Tokyo population	1.2	0.2	0.95	1800	9000	81023	90023	4052
Domestic spectators	0.7	-	-	-	268	189	457	10
Domestic spectators	1.2	-	-	-	268	338	606	17
2-group scenario								
Games accredited	0.7	0.2	0.99	1200	90	160	250	8
Games accredited	1.2	0.2	0.95	1800	130	1032	1162	52
Tokyo population	0.7	0.6	0.95	1200	6000	11643	17643	583
Tokyo population	1.2	0.6	0.95	1800	9000	80526	89526	4027

4. Discussion

In this study we used a multitype branching process model to perform a scenario analysis looking at SARS-CoV-2 transmission with relation to the Tokyo 2020 Olympic Games. We demonstrated that given existing COVID-19 prevalence levels in Japan and other parts of the world, we could expect secondary cases across multiple generations among Games accredited individuals, the general Tokyo population, and domestic spectators (had the latter group been permitted). According to our model, transmission was expected to be highly related to local transmission dynamics in Tokyo.

There are several aspects of the Tokyo 2020 OPG that make them unique among mass gatherings in the COVID-19 era, though perhaps not other sports competitions. First, the Games continue long enough for multiple generations of transmission to occur. Second, even compared to other world sports competitions, the Olympics are truly international, with athletes from nearly every country in the world participating. Third, coordinating the OPG in a host country with levels of transmission high enough to require an SoE declaration resulted in constantly changing guidelines and uncertainty that may have hindered efforts to implement safe infection prevention and response efforts at the Games and in the host city population.

The SoEs and quasi-SoEs implemented in 2021 focused on the early or complete closure of restaurants and stores, limiting the sales of alcohol and crowd size at venues, as well as asking people to limit non-essential outings, cease inter-prefecture travel, work from home, and wear masks [16]. Nonetheless, these measures were insufficient to prevent emergence of a fifth wave of COVID-19 transmission in Japan, and the number of newly infected cases grew during the weeks preceding the

Olympics opening ceremony.

We endeavored to estimate realistic relative population sizes and initial number of cases for each of the three groups for reconstruction of the NGM and use in the branching process models. However, there were only inexact reports of the number of people who would be involved in the Games prior to their start [8], and we were unable to find updated reports on the number of domestic Games accredited individuals post-hoc. As well, we had no indication of how many Games accredited individuals would be in the Tokyo area vs venues in other parts of Japan, so the overall population size of Games accredited individuals is likely an overestimate of the number who would be involved in the Games specifically in Tokyo.

Our estimates of the initial number of cases among foreign arrivals who would escape detection at the airport based on worldwide prevalence, vaccination status, and antigen test sensitivity were also likely underestimates. Multiplying the reported likely number of arrivals (~42,000) by our calculation of worldwide COVID-19 prevalence (see Supplementary Materials for details) and not discounting for vaccination, we estimated a maximum of twenty-two individuals would arrive in Japan infected. This is ten individuals fewer than the thirty-two who were reported positive at the airport (Figure 2C) during the analysis period [17]. Although quarantine should have effectively reduced onward transmission for undetected cases, many foreign Games accredited individuals were exempted from a full 14-day quarantine [5]. Due to the reporting practices by Tokyo 2020, we were also unable to reconcile the dataset on arrivals who tested positive at Narita Airport with the linelist dataset of cases. Therefore, our Figure 3 which shows the number of reported cases by generation includes cases found positive at the airport, though they should not be included because they would have been immediately isolated and therefore removed from the Games transmission dynamics.

Foreign athletes and officials participating in the Games underwent strict testing requirements, but this was not necessarily the case for other foreign Games accredited individuals. Many domestic Games accredited individuals were also unlikely to be tested more often than every 4 or 7 days—if they were tested at all [5]. On average, ~31,000 tests were completed each day during the Games (Figure 2B). Although we only assessed the Olympic Games, the Paralympic Games could have also been modeled using these methods. In addition, when considering spectator-related transmission we did not distinguish between open- vs closed-air venues, which could influence transmission dynamics between spectators. Open-air venues account for 14 of the 25 venues in Tokyo and 40% of spectators would have been at open-air venues.

Overall, our results where $R_b = 0.7$ provided the best approximation of the reported cases in the Games accredited individuals group indicates that the infection prevention measures imposed on these individuals, along with the requirement for frequent testing for many (though not all) of the population, provided enough control to keep transmission below epidemic levels. However, the Games-associated population involved constant immigration and emigration that could not be fully captured in our model due to a lack of information about the number of persons involved and timing of entrance and exit from the population dynamics. That $R_b = 1.2$ provided the best approximation of Tokyo cases indicates that increases in contact and the gaining predominance of the more transmissible Delta variant [11,18] may have been responsible for the large surge of cases within the Tokyo population. In addition, an abrupt peak of the reported effective reproduction number was observed during the 4-day consecutive holiday period (July 22–25) that coincided with the beginning of the Olympic Games, implying that the increase in the COVID-19 incidence of Tokyo population might be also driven by the elevated mobility during this holiday period [19].

5. Conclusions

Despite extraordinary planning and precautions more than five hundred Olympic Games accredited individuals were infected just before or during the Games. Stricter infection prevention guidance and better adherence to such guidance may have been able to reduce spread among these individuals after immigration to the Games accredited population (arrival in Tokyo and beginning of Games-associated duties). However, with the pandemic uncontrolled both in Tokyo and abroad, complete suppression of transmission was unlikely given the nature of the OPG as they involve intense physical exertion, close contact, and—inevitably—cheering on athletes who are doing their best to take home Olympic gold. Suppressing local transmission and encouraging risk-aware behavior is key to limiting the impact of mass gathering events such as the OPG on COVID-19 spread.

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Conflict of interest

The authors declare no conflicts of interest.

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