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Material:

COVID-19 Outbreak Forecasting and Effects of Self-Restraint Against Excursions in Tokyo, Japan, as of the End of March, 2020, Before the Emergency Declaration on April 7, 2020

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In Tokyo, Japan, coronavirus disease 2019 (COVID-19) cases have been increasing gradually since late March 2020. This study was aimed to predict the effects of self-restraint against excursions in Tokyo before the emergency declaration of April 7, 2020. Data of symptomatic patients collected between January 14 and March 28, 2020, in Tokyo, were used to formulate a susceptible–infected–recovered (SIR) model using three age classes and estimate the basic reproduction number (R_0). Based on the estimated R_0, we inferred outbreak outcomes and medical burdens if self-restraint against excursions had not been enacted. Thereafter, we estimated the effects of self-restraint against excursions. The results suggested an R_0 value of 2.86, with a 95% confidence interval of 2.73–2.97. It is likely that the exhaustion of medical resources could have occurred on April 28, 2020, if no self-restraint against excursions had occurred. If self-restraint against excursions had been enacted from April 6, 2020, and more than 60% of trips outside the home had been restricted voluntarily, medical care services would then have been predicted to be maintained. Our suggestion might have contributed to countermeasures against COVID-19 in Tokyo.

Keywords: coronavirus disease 2019, intensive care unit (ICU) beds, susceptible–infected–recovered (SIR) model, exhaustion of medical resources, post evaluation for forecast

1. Introduction

The initial case of coronavirus disease 2019 (COVID-19) in Japan was that of a patient who showed symptoms upon returning from Wuhan, China, on January 3, 2020. As of March 28, 2020, 1,150 cases of infection had been announced in the community of Japan, excluding asymptomatic cases, those for which the onset date or age was not reported, those infected abroad, and those infected on a large cruise ship: The Diamond Princess [1].

In metropolitan Tokyo, which has approximately 14 million residents, 234 symptomatic cases were identified as of March 28, 2020. The entire course of the outbreak was predicted to have been instrumental in projecting the necessity for medical resources, thereby guiding policymaking. Moreover, it was necessary to evaluate, as a worst-case scenario, the possible exhaustion of medical resources when medical needs far exceed the capacity of medical resources. In particular, intensive care unit (ICU) facilities do not operate with large surplus capacity. The facilities were expected to be allocated timeously to patients.

To forecast these phenomena at that time, we constructed a simple susceptible–infected–recovered (SIR) model for Tokyo as of the end of March, 2020. Thereafter, we predicted whether the exhaustion of medical resources would occur. Moreover, we predicted the effects of a self-restraint policy against excursions in Tokyo, as stipulated in the emergency declaration of April 7, 2020 and assessed whether medical care would be maintained.

2. Methods

We applied a simple SIR model [2–4] with three age classes: children 19 years old or younger, adults 20–59 years old, and elderly people 60 years old or older. We assumed that there was some level of protection for children [5], as 40% of children were protected from infection [2]. The incubation period was assumed to be equal for all people in the three age classes. It followed the empirical distribution inferred for the outbreak in Japan for the exposed and onset dates published by the Ministry of Health, Labour and Welfare (MHLW) [1].

Experience of Japanese people living in Wuhan was utilized. Between January 29 and February 17, 2020, 829 Japanese people returned to Japan from Wuhan. They underwent tests to detect severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), and 14 of them tested positive for SARS-CoV-2 [6]. Of these 14 people, 10 exhibited mild symptoms, whereas the other four showed no symptoms. Moreover, two Japanese residents of Wuhan exhibited severe symptoms, one of whom was confirmed to have contracted COVID-19. The other died, although no fatal case was confirmed as COVID-19 by testing. In addition, two Japanese residents of Wuhan with mild symptoms were denied re-entry into Japan, even though they had not been confirmed as infected. If one were to assume that the fatal case of the Japanese person in Wuhan and the two prohibited reentrants were infected with COVID-19, then two severe cases, 12 mild cases, and four asymptomatic cases were found to exist among these Japanese residents of Wuhan. Therefore, we applied this ratio of asymptomatic cases to symptomatic cases in the simulation.

We also assumed that the degrees of infectivity among the severe and mild patients were equal. In addition, the degree of infectivity among asymptomatic cases was assumed to be half of that in symptomatic cases. This assumption of relative infectiousness among asymptomatic cases compared with that among symptomatic cases was also used in simulation studies for influenza [7–11].

Contact patterns among children, adults, and elderly people were estimated in an earlier study [12]. We identified the following contact patterns: child–child contacts were $15/19$, child–adult $3/19$, child–elderly $1/19$, adult–child $3/9$, adult–adult $5/9$, adult–elderly $1/9$, elderly–child $1/7$, elderly–adults $2/7$, and elderly–elderly $4/7$ of all contacts.

We sought to ascertain the basic reproduction number (R_0) to fit the number of patients identified between January 14 and March 28, 2020, and to minimize the sum of squared residuals among the bootstrapped empirical epidemic curve and the predicted number by the model, given a value of R_0. We grid searched R_0 in the region of (0.01, 5.00) by 0.01. Its 95% confidence interval (CI) was calculated using 10,000 iterations of bootstrapping for the empirical distribution of epidemic curves. These procedures were similar to those used in earlier studies [4, 13].

We assumed that contact frequencies in the same age class would decrease by the same proportion in all age classes if self-restraint against excursions in Tokyo were to be declared. However, contact frequencies between different age classes were assumed not to be changed by self-restraint against excursions because most contact with other age classes can be presumed to have occurred at home. Contacts at home were expected to be unaffected by self-restraint from excursions.

Experience in Japan has revealed that the incidence of pneumonia among elderly COVID-19 patients is 28%, whereas that among adults is 20%, based on national data in Japan obtained as of March 23, 2020, as published by MHLW [1]. We used these ratios to infer the ratios of severe cases to symptomatic cases. Among children, no cases of pneumonia have been reported. Only pneumonia cases were assumed to receive hospital treatment. The length of hospitalization was assumed to be 30 days. Of those pneumonia cases, 30% were assumed to require ICU facilities for 20 days.

However, if patients requiring care in an ICU could not receive it, then we assumed that the case-fatality rate among them would be 100%. By defining the "exhaustion of medical resources" as a demand for ICU beds greater than 70% of all existing ICU beds and assuming 1,000 ICU beds in Tokyo, an ICU-bed demand of greater than 700 would signal a medical service crisis.

We used data from the COVID-19 community outbreak of patients in Japan who showed any symptoms between January 14 and March 28, 2020, in Tokyo. We excluded patients who had been infected abroad and had returned as well as those who were presumed to have been infected whilst on board the Diamond Princess. They were presumed as not to be community-acquired cases in Japan.

Published information regarding symptomatic COVID-19 patients from the MHLW in Japan or metropolitan Tokyo was usually affected adversely by some delay due to the uncertainty of the duration from onset to first doctor's visit or that of the timing of a physician's suspicion of COVID-19. Therefore, the published patient data must be adjusted by at least a few days.

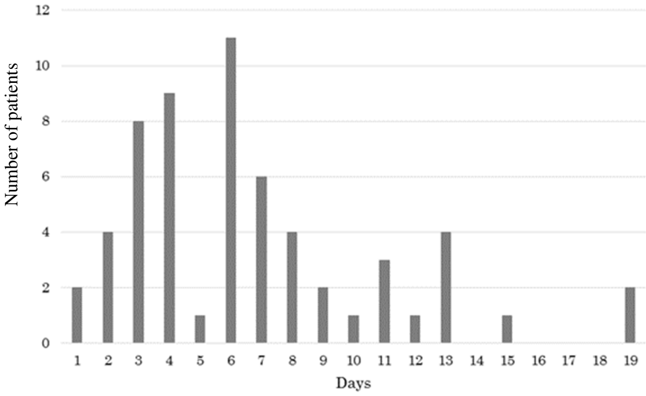
To adjust the data, we applied the following regression analysis: We set $Xt-k|t$ as the number of patients for whom the onset date was $t-k$ published on day t. The dependent variable is the degree of reporting delay, $Xt-k-m|t/Xt-k-m|t-m$, where $k>m$ for several m and k. Here, m denotes the difference between the publishing date in the past and the most recent publishing date. Date t represents the publishing date of the latest publication.

The explanatory variables were $1/k$, $1/m$, and $1/km$. The degree of reporting delay was estimated as (estimated coefficient of constant term) + (estimated coefficient of $1/k)/k$ for sufficiently large m and when sufficient time had passed. Therefore, this estimated degree of reporting delay multiplied by the latest published data is expected to be a prediction of the number of patients for whom the onset date was $t-k$. We used this adjusted number of patients for the most recent few days. We used data provided by the MHLW for March 2, 6, 10, 12, and 14, 2020 [1]. We used a significance level of 5%.

After estimating R_0, we predicted the total number of symptomatic patients, maximum number of newly symptomatic patients per day, maximum number of inpatients, and maximum number of patients needing ICU beds. We also predicted the date of exhaustion of medical resources. Moreover, we predicted the effects of self-restraint from excursions from April 6, 2020, and assessed whether medical system services would be maintained. We calculated 95% CIs through 10,000 bootstrapped distributions.

Ethical Consideration

All information used in this study was collected within the confines of the Law of Infection Control, Japan. Therefore, no ethical issue exists related to this study.



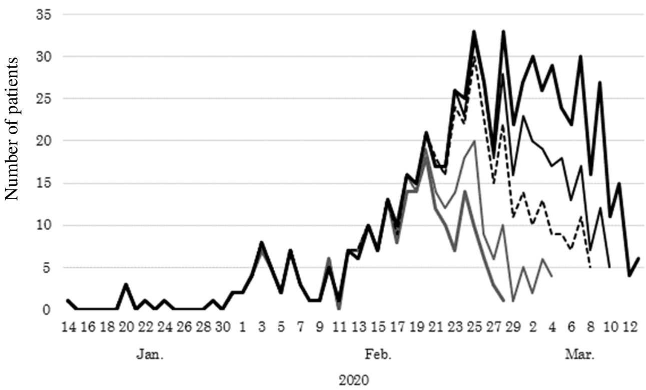
Note: Bars represent the number of patients by incubation period among 59 of 62 cases whose exposure and onset dates were published by the Ministry of Health, Labour and Welfare, Japan.

Fig. 1. Empirical distribution of incubation period published by the Ministry of Health, Labour and Welfare, Japan.

Table 1. Estimation results of the degree of reporting delay.

	Estimated coefficient	p-value	95% confidence interval	
			Lower	Upper
$1/k$	16.9	0.000	14.7	19.0
$1/m$	1.01	0.025	0.14	2.05
$1/(km)$	−21.8	0.000	−26.7	−16.9
Constant	0.266	0.236	−0.175	0.707

Note: The number of observations was 323. The coefficient of determination was 0.457. k denotes the number of days until the last reported day. m denotes the difference between the publishing date in the past and the most recent publishing date. The dependent variable is the degree of reporting delay, which is defined as $Xt-k-m|t/Xt-km|t-m$, where $Xt-k|t$ is the number of patients for whom the onset date was $t-k$ published on day t. We used the number of patients by onset day published on March 2, 6, 10, 12, and 14, 2020, by the Ministry of Health, Labour and Welfare, Japan.



Note: The black bold, black thin, broken, gray thin, and gray bold lines show epidemic curves based on their onset dates as published on March 14, 12, 10, 6, and 2, 2020, respectively, by the Ministry of Health, Labour and Welfare, Japan.

Fig. 2. Epidemic curves of coronavirus disease 2019 in Japan published on March 2, 6, 10, 12, and 14, 2020, by the Ministry of Health, Labour and Welfare, Japan.

3. Results

Between January 14 and March 28, 2020, in Tokyo, four cases among children, 145 among adults, and 85 among elderly people were identified as community-acquired COVID-19 for whom the onset date was published. **Fig. 1** depicts the empirical distribution of the incubation period among 59 of 62 cases for which the exposed and onset dates were available. Its mode and median were each six days; the mean was 6.74 days.

Figure 2 depicts the epidemic curves published for March 2, 6, 10, 12, and 14, 2020. From this information, we estimated the degree of reporting delay. These results are presented in **Table 1**. The table shows that $1/k$, $1/m$, and $1/(km)$ are all significant. When m is sufficiently large, the effects of $1/m$ and $1/(km)$ converge to zero. Therefore, the estimated degree of reporting delay consists of the term $1/k$ and a constant term. Based on these results, we predict the degrees of reporting delay as 19.3 for $k=1$, 9.64 for $k=2$, 6.42 for $k=3$, and so on.

The R_0 values were estimated as 2.86 and 95% CI (2.73, 2.97). The outcomes, presented in **Table 2**, show that the total number of patients with any symptoms was estimated to be 6.41 (6.38, 6.47) million. The maximum number of patients with new onset was estimated to be 0.117 (0.115, 0.120) million per day at the peak. At the peak, the maximum number of patients with pneumonia was estimated to be 0.776 (0.766, 0.796) million. Moreover, the maximum number of patients needing ICU beds was estimated to be 0.180 (0.180, 0.187) million. Finally, the results show that 70% of ICU capacity would have been exceeded on April 28 (26, 29), 2020.

The results for the prediction of the effects of self-restraint against excursions from April 6, 2020, are presented in **Table 3** according to the proportion of self-restriction of people leaving their home. The exhaustion of medical resources would be prevented if more than 60% of trips outside the home was to be restricted. The exhaustion of medical resources would be postponed by three months if more than 50%, but fewer than 60%, of trips outside the home were to be restricted.

4. Discussion

We applied a simple SIR model to three age classes, including asymptomatic cases, assuming that a considerable proportion of children was protected. An earlier study estimated R_0 for COVID-19 as 2.24–3.58 in Wuhan [14–16], which was similar to our R_0 value of 2.86. However, one study revealed R_0 in Japan up to February 26, 2020, as just 0.6 [17]. This number indicates that no large outbreak would have emerged in Japan, except for sporadic cases, and medical resources would never have been exhausted.

Because R_0 was defined with no countermeasure or immunity, an exhaustion of medical resources could not be

Table 2. Prediction of coronavirus disease 2019 patients and date of exhaustion of medical resources in Tokyo.

	Median	95% confidence interval (CI)	
		Lower	Upper
Total number of symptomatic patients (in millions)	6.41	6.38	6.47
Maximum number of newly symptomatic patients per day (in millions)	0.117	0.115	0.120
Maximum number of inpatients (in millions)	0.776	0.766	0.796
Maximum number of patients needing ICU beds (in millions)	0.180	0.180	0.187
Date of exhaustion of medical resources (the year 2020)	April 28	April 26	April 29

Note: This table presents simulation results that can be expected without self-restraint against excursions. The 95% CIs were estimated through 10,000 iterations of bootstrapping. "Exhaustion of medical resources" was defined as a demand for ICU beds greater than 70% of all existing ICU beds.

Table 3. Predicted effects of self-restraint against excursions in Tokyo from April 6, 2020, as measured by the date of exhaustion of medical resources.

Proportion of self-restraint against excursions [%]	Date of exhaustion of medical resources (the year 2020)	95% confidence interval	
		Lower	Upper
0	April 28	April 26	April 29
5	April 30	April 28	May 1
10	May 2	April 20	May 3
15	May 5	May 2	May 6
20	May 8	May 5	May 10
25	May 12	May 9	May 14
30	May 17	May 13	May 20
35	May 25	May 20	May 28
40	June 5	May 29	June 8
45	June 24	June 14	June 29
50	July 30	July 13	August 8
55	October 20	September 3	November 21
> 60	No exhaustion of medical resources		

Note: "Exhaustion of medical resources" was defined as a demand for ICU beds greater than 70% of all existing ICU beds.

avoided if insufficient or no countermeasures were taken. On April 28, 2020, medical services were expected to be critical. The results also demonstrate that if a policy of self-restraint against excursions was initiated on April 6, 2020, and more than 60% of outings were restricted voluntarily, medical care would then have been maintained. It is noteworthy that Japan used no law to enforce curfews. Therefore, self-restraint policies were intended to urge residents, not force them, to avoid leaving their homes voluntarily. Consequently, the enactment of a self-restraint policy must achieve a great degree of voluntary cooperation.

Evidence related to compliance is scarce because no lockdown has been enforced in Japan to date. A survey conducted in one exceptional study asked people about restricting movement outside the home if the government asked them to do so [18]. The results showed that 93.3% would comply voluntarily with such a government request. In Japan, even with no enforcement of a lockdown, the exhaustion of medical resources by COVID-19 may be avoided because strong policy compliance can be expected.

Research conducted online ahead of printed reports suggests that school closure since March 2, 2020, decreased contact frequency among children by 40% [13]. Voluntary event cancellation from February 27 decreased contact frequency among adults by 50%. Although exhaustion of medical resources has been postponed for a while, it appears to be unavoidable eventually because a 50% reduction in infectiousness is still lower than the 60% proportion of self-restraint against excursions that is predicted to guarantee no exhaustion of medical resources.

The SIR model is too simple to incorporate data for households, firms, and schools. It is a completely mixed model. Therefore, it ignores some differences inside and outside of those groups. Contact patterns can be adjusted to reflect the effects of some policies, including self-restraint against excursions, as in the present study.

A model highlighting differences inside and outside these groups is an individual-based model (IBM), which incorporates movements and contacts of individuals. It can be used to evaluate behavioral changes in individuals directly [7–10, 19]. Therefore, the IBM should be used for the evaluation of self-restraint against excursions instead of the SIR model.

No IBM exists for COVID-19; however, an IBM exists for pandemic influenza. The most precise and real IBM has been developed in Japan using actual transportation data [18, 19]. Results have indicated that a 60% voluntary restriction against excursions can reduce the prevalence of pandemic influenza by 40 percentage points [19]. Therefore, it produces the same result as that of the present study for COVID-19, specifically, 60% voluntary restriction against excursions can forestall exhaustion of medical resources.

Some limitations may affect the results and generality of this study. Foremost is the definition of the "exhaustion of medical resources," which we defined as a demand for ICU beds exceeding 70% of capacity. This limit implies that the utilization of beds or the length of stay in ICU beds by non-COVID-19 patients should be reduced because the average utilization of ICU beds before the COVID-19 outbreak was approximately 70% [20]. Our definition seems to be a reasonable assumption; nevertheless, we are unable to confirm its veracity or feasibility. For this study, there was insufficient time to consider other definitions with a limit lower than 70% to provide some prediction by April 7, 2020; however, a more accurate limit is a challenge to be addressed by future research. Moreover, some evidence to help define the exhaustion of medical resources must be considered. This point is also reserved as a subject for further study.

Assumptions regarding hospitalization or the ICU, such as length of stay and proportion of patients who need ICU care, are also limitations. They must be verified. These parameters must be monitored carefully over an entire course of the outbreak.

5. Conclusions

We described the prediction of the COVID-19 outbreak and the effects of self-restraint against excursions in Tokyo as of the end of March, 2020, before the emergency declaration on April 7, 2020. The first version of the present study was uploaded to a website on April 6, 2020 [21], where it probably influenced decisions regarding the emergency declaration of April 7. The information was perhaps used as one piece of evidence for recommendations concerning self-restraint against excursions during the emergency. The consideration of this contribution in government decision-making regarding countermeasures against COVID-19 will be important for future studies and policies.

This study represents the authors' opinions. It does not reflect any stance of our affiliation.

Competing interest

No author has any conflict of interest, financial or otherwise, to declare in relation to this study.

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