Forecast of the COVID-19 outbreak, collapse of medical facilities, and lockdown effects in Tokyo, Japan

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Running title: Collapse of medical facilities and lockdown due to COVID-19

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Abstract

Background: The number of patients of COVID-19 in Tokyo has been increasing gradually through the end of March, 2020.

Object: Support for policymaking requires forecasting of the entire course and outcome of the outbreak including the date of collapse of medical facilities if a lockdown is not initiated. Moreover, the effects of a lockdown must be considered when choosing to initiate one.

Method: Data of Tokyo patients with symptoms during January 14 – March 28, 2020 were used to formulate a susceptible–infected–recovered (SIR) model using three age classes and to estimate the basic reproduction number (R_0). Based on the estimated R_0, We inferred outbreak outcomes including the date of collapse of medical facilities if a lockdown were not enacted. Then we estimate the lockdown effects.

Results: Results suggest R_0 as 2.86, with a 95% confidence interval of [2.73, 2.97]. Collapse of medical facilities can be expected to occur on April 26 if no lockdown occurs. The total number of deaths can be expected to be half a million people. If a lockdown were enacted from April 6, and if more than 60% of trips outside the home were restricted voluntarily, then a collapse of medical facilities could be avoided.

Discussion and Conclusion: The estimated R_0 was similar to that found from other studies conducted in China and Japan. Results demonstrate that a lockdown with reasonable cooperation of residents can avoid a collapse of medical facilities and save 0.25 million mortality cases.

Introduction

The initial case of COVID-19 in Japan was that of a patient who showed symptoms when returning from Wuhan, China on January 3, 2020. As of March 28, 2020, 1150 cases had been announced as infected 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 about 13 million residents, 234 symptomatic cases were identified as of March 28, 2020. The entire course of the outbreak must be predicted to evaluate the necessary medical resources for policymaking. Moreover, one must evaluate, as a worst case scenario, the collapse of medical facilities which can occur when medical needs far exceed the capacity of medical resources. Under such circumstances, the case-fatality ratio (CFR) rises considerably. Especially, the capacity of intensive-care-unit (ICU) facilities is usually not so large. They are expected to be allocated quickly to patients. Therefore, escalation of case mortality represents an important concern.

To forecast these phenomena, we construct a simple susceptible–infected–recovered (SIR) model for Tokyo incorporating the necessary medical resources. Then we predict whether a collapse of medical facilities occurs, in addition to the magnitude of mortality if a collapse were to occur.

Method

We applied a simple SIR model [2,3,4] 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 some protection of children [5]: 40% of children were protected t infection [4]. The incubation period was assumed to be equal for all people of the three age classes and following the empirical distribution inferred for the outbreak in Japan.

Experiences of Japanese people living in Wuhan until the outbreak provide information related to mild cases because complete laboratory surveillance was conducted for them. During January 29 – February 17, 2020, 829 Japanese people returned to Japan from Wuhan. Each had undergone a test to detect COVID-19; of them, 14 were found to be positive for COVID-19 [6]. Of those 14, 10 Japanese people had exhibited mild symptoms; the other 4 showed no symptom. Moreover, two Japanese residents of Wuhan exhibited severe symptoms: one was confirmed as having 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 refused re-entry to Japan even though they had not been confirmed as infected. If one assumes that the Japanese fatal case in Wuhan and that the two rejected re-entrants were infected with COVID-19, then 2 severe cases, 12 mild cases, and 4 asymptomatic cases were found to exist among these Japanese residents of Wuhan. We therefore apply these proportions of asymptomatic cases to symptomatic cases in the simulation.

Assuming that the degrees of infectivity among the severe patients and mild patients are equal also for asymptomatic cases, half of the symptomatic cases can be assumed. This assumption about relative infectiousness among asymptomatic cases compared with symptomatic cases was used also in simulation studies for influenza [7–11].

We sought to ascertain R_0 to fit the number of patients during 14 January – 28 March and to minimize the sum of squared residuals among the reported numbers and the fitted values. Its 95% confidence interval (CI) was calculated using 10,000 iterations of bootstrapping for the empirical distribution of epidemic curves.

Contact patterns among children, adults, and elderly people were estimated in an earlier study [12]. We identified the following contact patterns: the share of children contacting with other children accounted for 15/19 of all contacts, contact with adults accounted for 3/19, and contact with elderly people accounted for 1/19; the share of adults contacting children accounted for 3/9 of all contacts; those contacting with other adults were 5/9, and those contacting with elderly people were 1/9; elderly people contacting with children were 1/7, with adults were 2/7, and with other elderly people were 4/7.

We assumed that contact frequencies in the same age class decreased in the same proportion in all age classes if the Tokyo Metropolitan Government (TMG) were to declare a lockdown in Tokyo. However, contact frequencies among other age classes were assumed not to be changed by a lockdown because most of the contact with other age classes can be presumed to occur at home. Contacts at home will probably be unaffected by a lockdown.

Experience in Japan has revealed the pneumonia incidence in elderly COVID-19 patients as 30.6%. That among adults is 22.2%. We used these ratios to assume ratios of severe cases to symptomatic cases. Among children, no pneumonia case has been reported. Only pneumonia cases were received hospital treatment. The length of hospitalization was assumed as 30 days. Of those severe cases, 30% were assumed to require the use of an intensive care unit (ICU) and respirator for 20 days. The case fatality rate among ICU patients was assumed to be 50% from experience in Tokyo up through March 25, 2020.

However, if patients requiring care at an ICU or respirator cannot receive it, then we assumed that the CFR among them was 100%. We define the *collapse of medical facilities* as circumstances under which the necessary ICU bed number becomes greater than 70% of all existing ICU beds. In Tokyo, there are 1000 ICU beds. Therefore, if the necessary number of ICU beds becomes greater than 700, medical service at the facilities will collapse. The CFR among patients who need care at an ICU but do not receive it is 100%.

We used data of the COVID-19 community outbreak of patients in Japan who showed any symptom during January 14 – March 28, 2020 in Tokyo. We excluded some patients who had been infected abroad and who returned from abroad and those who were presumed to be infected persons from the Diamond Princess. They were presumed not to be community-acquired in Japan.

Published information about COVID-19 patients with symptoms from the Ministry of Labour, Health and Welfare (MLHW) Japan or TMG was usually affected adversely by some delay because of uncertainty during onset to visiting a doctor or in the timing of a physician's suspicion of COVID-19. Therefore, published data of patients must be adjusted 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 variables are 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 of the publishing dates between the two published. Date *t* represents the publishing date of the latest publishing. 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*, when *m* was sufficiently large and 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 in the latest few days, including those after VEC was adopted. We used published data of 2, 5, 6 and 9–17 March, 2020 provided by MLHW [1].

First, we estimated R_0. Then we predicted the peak date, total number of symptomatic cases and mortality cases, maximum number of newly infected symptomatic cases per day, beds, and ICU beds. We also predicted the date of collapse of medical facilities. Moreover, we predicted the effects of the lockdown from April 6 and measured whether the medical system would collapse. Then for cases of collapse, we inferred the date of collapse. We calculated the 95% CI through 10,000 bootstrapped distributions.

Ethical consideration

All information used for this study has been collected under the Law of Infection Control, Japan. There is therefore no ethical issue related to this study.

Results

During January 14 – March 28 in Tokyo, 4 cases among children, 145 cases among adults, and 85 cases among elderly people were identified as community-acquired COVID-19 for whom the onset date was published. Figure 1 depicts the empirical distribution of incubation period among 62 cases for which the exposed date and onset date were published by MHLW. Its mode and median were six days; the average was 6.74 days.

Figure 2 depicts epidemic curves published for 2, 5, 6, 10, 11, 12, 13, and 14 March. From this information, we estimated the degree of reporting delay. Those 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 of $1/k$ 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 protection level was estimated as 0.4 [0.2, 0.7]. Outcomes, presented as Table 2, show that the total number of patients with any symptom was estimated as 6.41 [6.48, 6.57] million. The maximum number of patients with new onset was estimated as 0.777 [0.766, 0.796] million per day at the peak. At the peak, the maximum number of the administered patients with pneumonia was estimated as 0.180 [0.180, 0.187] million per day. Moreover, the maximum number of patients who need an ICU bed and respiratory assistance was estimated as 0.496 [0.494, 0.501] million per day. Results show that 70% of ICU capacity will be exceeded on 28 [26,29] April. Finally, the total number of mortality cases would be 0.496 [0.494, 0.501] million. Results of the lockdown are presented in Table 3 according to the proportion of voluntary restriction of people leaving their home. A collapse of medical facilities could be prevented if more than 60% of trips outside of the home were restricted. The collapse of medical facilities could e postponed by three months if more than 50% but fewer than 60% of trips outside of the home going were restricted.

Discussion

We applied a simple SIR model with three age classes including asymptomatic cases and assuming some proportion of children as protected. An earlier study [13–15] estimated R_0 for COVID-19 as 2.24–3.58 in Wuhan. Our obtained R_0 of 2.86 was very similar. However, one study revealed that R_0 in Japan up through 26 February was just 0.6 [16]. Their evidence given was the number of secondarily infected people. Of 110 primary cases, they found that 83 cases did not infect anyone.

Nevertheless, their findings must be considered carefully. They specifically examined only those patients who had been infected by the known confirmed cases. However, half of the patients had no link to any known confirmed case. They were probably counted as primary cases but not as secondary cases. They were infected by someone in the community. In fact, until 26 February, there were 302 infected persons in the community. Of those, 161 cases were unlinked. Therefore, those unlinked 161 cases were actually secondary cases that had not appeared as secondary cases in the figures of an earlier study [14].

One might assume that the primary cases which proceeded to infect the unlinked secondary cases were the same as the 110 primary cases in an earlier study. If so, then R_0 should be 2.1 (=0.6+161/110). Alternatively, one can infer that the primary cases of the unlinked patients were not identified by a public health center (PHC) and that their distribution of the secondary cases was the same as the figure in an early study. That would mean that 28 primary cases infected 66 secondary cases. Therefore, the average number of secondary cases conditional on those which infected more than one person was 2.44 (=66/27). Presumably, the 161 unlinked cases were infected by 66 hypothetical primary cases. Moreover, these hypothetical 66 cases represented infection by 27 other cases, and so on. Therefore, 112 cases infected 273 cases which were not identified by a PHC. In total, the average number of secondary cases is expected to be 1.5 (=(66+273)/(110+112)). Therefore, the true number of R_0 is expected to be in the range of 1.5–2.1. These numbers are slightly smaller than other estimates, but far greater than one.

Moreover, on April 26, medical services can be expected to collapse. Eventually, the cases ending in mortality will be approximately 0.5 million in Tokyo if no lockout is conducted. The number of deaths will be about five times greater than the average number of deaths during an equivalent period. Results also demonstrate that if a lockdown is initiated on April 6 and if more than 60% of trips outside the home were restricted voluntarily, then collapse of medical facilities might be avoided. It is noteworthy that no law exists to enforce curfews in Japan. Therefore, a lockout would ask, not force, residents to avoid leaving their home voluntarily. Consequently, cooperation with a lockout must achieve voluntary cooperation to a great degree. Evidence related to compliance is scarce because no lockdown has been conducted in Japan to date. An exceptional study asked people about restricting movement outside the home if the government asked them to do it [17]. Results showed that 93.3% would comply voluntarily with such a government request. Collapse of medical facilities from COVID-19 might be avoided in Japan, even with no enforcement of a lockdown, because strong compliance can be expected.

Our unpublished research suggests that school closure since March 2 decreased contact frequencies among children by 40%. Voluntary event cancellation since February 27 decreased it among adults by 50%. Although a collapse of medical facilities has been postponed, it appears to be unavoidable if we apply these numbers to a lockdown effect.

The SIR model is too simple to incorporate households, firms or schools. It is a completely mixed model. It therefore ignores some difference inside and outside of those groups. It can adjust contact patterns to mimic some policies including lockdowns or school closures as in the present study. A model highlighting differences inside and outside of those groups is an individual-based model (IBM), which mimics movements and contacts of individuals. It can therefore evaluate behavioral changes of individuals directly [6–9,17]. Therefore, we must use IBM for evaluation of a lockdown instead of a SIR model. No IBM exists for COVID-19 but an IBM exists for pandemic influenza. Especially, the most precise IBM, RIBM, has been developed in Japan using actual data of transportation [17, 18]. It indicated that lockdown with 60% voluntary restriction to going out can reduce prevalence by 40 percentage points for pandemic flu [18]. Therefore, it shared the same result that 60% voluntary restriction out of trips outside the home can avoid collapse of medical facilities with the present study for COVID-19.

Conclusion

We predicted outcomes of COVID-19 and lockdown effects in Tokyo. We estimated a collapse of medical facilities in late April and about 0.5 million cases with mortality in Tokyo if a lockdown were not applied. We estimated the effects of lockdown enacted from April 6 and reasonable compliance with voluntary restrictions on trips outside the home. Such a lockdown might avoid a collapse of medical facilities. However, it is noteworthy that such a lockdown might continue until a vaccine for COVID-19 can be developed. Costs of a lockdown would be huge if it were to last for more than a half of year. Its cost-effectiveness is expected to represent a concern in this case. This study represents the authors' opinion. It does not reflect any stance of our affiliation.

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Table 1: Estimation results of the degree of reporting delay

	Estimated coefficient	*p*-value	95%CI	
			Lower bound	Upper bound
$1/k$	16.9	.000	14.7	19.0
$1/m$	1.01	.025	0.140	2.05
$1/(km)$	-21.8	.000	-26.7	-16.9
Constant	0.266	.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 among of reporting delay, which is defined as $Xt\text{-}k\text{-}m|t$ / $Xt\text{-}k\text{-}m|t\text{-}m$, where $Xt\text{-}k|t$ 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 2, 5, 6, 10, 11, 12, 13, and 14 March 2020 by the Ministry of Labour, Health and Welfare, Japan.

Table 2: Prediction of patients and necessary medical resources in Tokyo (in thousands)

	Median	95%CI	
		Lower	Upper
Total number of symptomatic patients	6410	6380	6470
Maximum number of newly symptomatic patients per day	117	115	120
Maximum number of inpatients	776	766	796
Maximum number of necessary ICU patients	180	180	187
Total number of mortality cases	496	494	501
Date of medical system collapse	April 28	April 26	April 29

Note: This table presents simulation results that can be expected without lockdown. 95% CI was estimated both through 10,000 iterations of bootstrapping. Collapse of medical facilities was defined as necessary ICU beds greater than 70% of capacity.

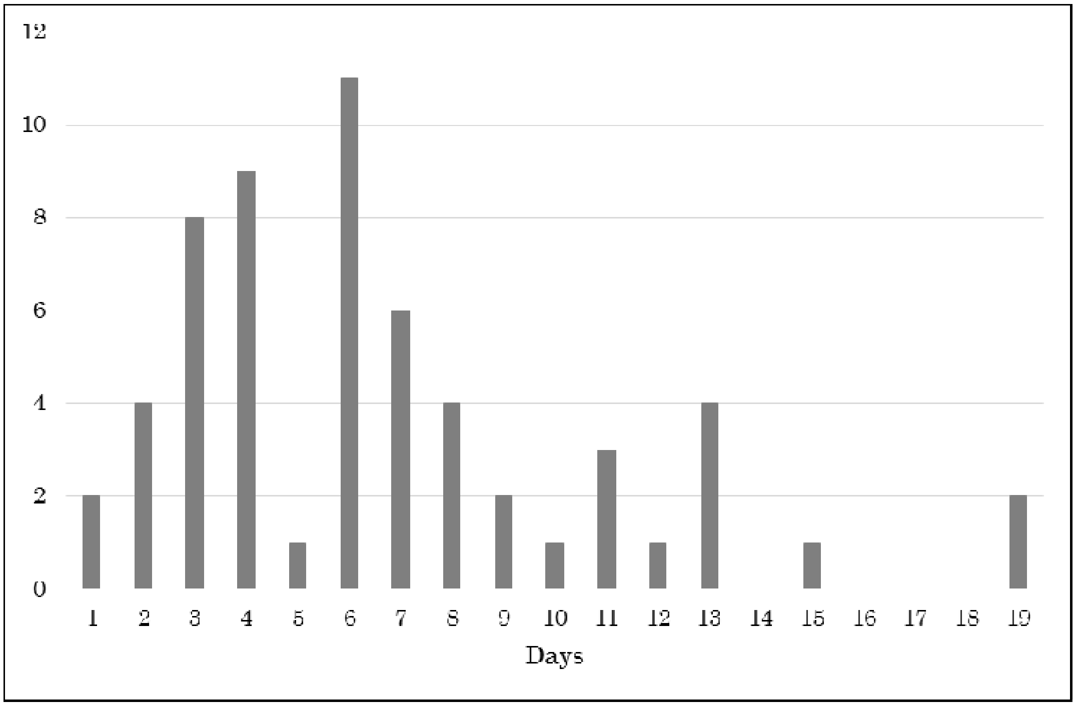
Table 3: Predicted effects of lockdown in Tokyo as measured by date of medical facilities collapse

Proportion of voluntary restriction of going out (%)	Estimation	95%CI	
		Lower	Upper
0	28 April	26 April	29 April
5	30 April	28 April	1 May
10	2 May	20 April	3 May
15	5 May	2 May	6 May
20	8 May	5 May	10 May
25	12 May	9 May	14 May
30	17 May	13 May	20 May
35	25 May	20 May	28 May
40	5 June	29 May	8 June
45	24 June	14 June	29 June
50	30 July	13 July	8 August
55	20 October	3 September	21 November
>60	No collapse of medical facilities		

Note: “Collapse of medical facilities” is defined as necessary ICU beds greater than 70% of capacity.

Figure 1: Empirical distribution of incubation period published by Ministry of Labour, Health and Welfare, Japan

(number of patients)



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