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Estimating Effectiveness of Preventing Measures for 2019 Novel Coronavirus Diseases (COVID-19)

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***Abstract*—This paper implements the infection process of 2019 Novel Coronavirus Diseases (COVID-19) in an agent-based model and compares the effectiveness of multiple infection prevention measures. In the model, 1120 virtual residents agents live in two towns where they commute to office or school and visiting stores. The model simulates an infection process in which they were exposed to the risk of transmission of the novel coronavirus. The results of the experiments showed that individual infection prevention measures (commuting, teleworking, class closing, contact rate reduction, staying at home after fever) alone or partially combined them do not produce significant effects. On the other hand, if comprehensive measures were taken, it was confirmed that the number of deaths, the infection rate, and the number of severe hospitalised patients per day was decreased significantly at the median and maximum respectively.**

***Index Terms*—2019 Novel Coronavirus Diseases, COVID-19, infectious disease, agent-based model, preventing measures**

I. INTRODUCTION

The novel coronavirus (COVID-19), which appeared in Wuhan, Hubei Province, China around December 2019, spread rapidly throughout China, with cases reported in 31 provinces as of February, 2020 [1]. The infection spread throughout the world at the same time. As of early March 2020, over 4,000 deaths had occurred and cases in more than 110 countries had been confirmed, and the disease was declared a pandemic by the WHO. Japan has confirmed about 600 cases domestically and approximately 700 on cruise ships. In this context, various measures for the prevention of infection have been presented by the Japanese Ministry of Health, Labour and Welfare (MHLW), individual municipalities, research institutes, and the media. For example, the MHLW has recommended hand-washing with soap or alcohol-based sanitizers, covering one s mouth and nose with a mask or tissue when coughing or sneezing, avoiding public transit and crowded areas on the part of those with existing conditions, and so on. Elsewhere, corporations and municipalities have directed that various infection prevention measures be taken, instructing those with direct contact to work from home and recommending remote work, staggered work hours, and avoidance of excursions and face-to-face meetings.

Based on case studies from China [2], the Flow-SEIR model has been applied to estimate infection numbers and their results reported. According thereto, effects are estimated for the two factors of cutoff transit and quarantine, with the infection peak being reduced by close to 90% in the event of one week of quarantine in advance. About 21-22% reduction due to transit cutoffs is to be expected.

However, it is difficult to produce an overall estimate of the effects of COVID-19 on various infection prevention measures, such as remote work and closed schools, given the limited data. With regard to this issue, this paper uses an agent-based model of infection to report the results of a comparative estimation of these effects.

II. RELATED RESEARCH

A. Infection Simulation Models

Epstein [3], [4] created an infection model based on 49 incidences of smallpox infection, mainly in Europe, from 1950 to 1971; the model's simulation results were shown to match the actual infection data. This model designed two towns, comprising 200 households and 800 residents, as the agent-based model, simulating the spread of an infectious disease.

Ohkusa was in favor of smallpox prevention measures using the infectious disease individual-based model [5]. The model imagines a town with 10,000 residents and a public health center, beginning with one person becoming infected with smallpox at a shopping mall and comparing vaccination measures through simulation. The results of the simulation show that when the diffusion rate at the initial infection stage is high and there are few medical staff members, the effects of follow-up vaccination decrease, but those of group vaccination are stable. In the case of measles infection, as a data-driven agent-based model to simulate the spread of airborne infection in a town in Ireland, a framework reconstructing epidemiological dynamics was used to develop an agent-based simulation model of measles transmission [6], [7].

B. Ebola and Rubella Models

The Ebola virus of West Africa in 2014 was a major tragedy which infected a total of over 28,600 victims and claimed the lives of 11,308 [8]. While the Ebola virus is highly infectious, it is thought to be transmitted through contact with a carrier's bodily fluids rather than as an airborne infection, which means that the risk of infection is high within a one-meter radius

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of carriers because of the danger of viral content in coughs or sneezes. Studies experimenting on the definition of the infection process, based on WHO investigation reports, have confirmed the efficacy of follow-up vaccinations in comparison to group vaccinations [9].

Studies on rubella have included in their models the differing antibody prevalence rates between men and women in Japan, in particular, as well as the need to consider the influence of workplaces where the genders are separate. The results indicated that the spread of infection is conjectured to begin in workplaces with many male employees without antibodies and that increasing the antibody prevalence rate among men was an important measure in the prevention of the overall spread of the infection.

C. Issues of Existing Research and Purposes of This Study

Based on these studies, the efficacy of the agent-based model has become clear; with regard to COVID-19, however, given the lack of people with immunity and the suggested possibility that infection may take place during the latency period, there has been almost no mention of the effects of remote work, staggered work hours, or avoidance of commercial facilities and crowds, even though plenty information on these issues has been released. Therefore, the purpose of this report is to engage in a comparative simulation experiment on the effects of preventive measures available to ordinary people, corporations, and schools, among others.

III. NOVEL CORONAVIRUS MODEL

As a base model, a comparatively abstract middle-range model was adopted. The purpose of this model is to reproduce the mechanism of the dynamic process of the phenomena and thus compare the effects of each scenario, rather than imitating a specifically detailed social phenomenon. Here, COVID-19 infection process will be mounted on the smallpox/Ebola model, Kurahashi 16, and the rubella model, considered highly valid in existing research on infectious diseases. The Ebola model, an extension of the Epstein model, has been shown to match the infection pattern of the 2014 Ebola outbreak in West Africa with regard to simulation results for trends in the number of infected cases, number of deaths, and number of recovered patients. The rubella model clarifies that a model taking into account the differing antibody prevalence rates between men and women can explain the recent rubella outbreaks in Japan and has been shown to match the actual outbreak ratios. This study applies the parameters relating to the infection process of COVID-19, as known as of early March 2020, to these models.

In the model used, there are two neighboring towns whose residents regularly commute to work or school and make use of commercial facilities. One town includes four-person households with children and two-person households comprising adults only. There are 100 four-person households with children, comprising two parents and two children each. There are 80 two-person households comprising adults only. A total of 560 people are in residence. There is one more town with the same composition for a total of 1,120 people in the model. Ten percent of the parents commute to different towns for work, while the others work in their own town during the day. All the children attend school. There is one shared hospital providing medical services, with five people from each town working there, forming a total of 10 people. Of the parents commuting to work, half use the train. The two-person households are considered to be of the elderly and thus do not commute to work. The adults among the residents are defined to visit commercial facilities, event locations, and other crowded areas on a regular basis at the probability sr.

Each round of the simulation is composed of the residents• overall interaction. The execution order is randomized, with resident agents activated sequentially. When the resident agent is activated in each round, interaction is generated by probability with rate of contactcr with neighbors in the Moore neighborhood (8 directions), generating infection in accordance with the transmission rate tr from the resident agent with whom there was contact. Here, the probability of infection is considered the incidence rate ir and defined as follows.

$$ir = cr * tr \tag{1}$$

Based on the Nakamura 2020 Environmental Infection 20 report with its detailed analysis of the COVID-19 outbreak, the infection process has been defined as follows. The latency period is, on average, five days from infection; however, infection of others is possible three days before the symptoms appear, during the latency period. On the 6th day, as the latency period ends, symptoms such as fever, cough, and diarrhea appear. After the fever appears, in the base model, there is a 50% probability of being examined at the hospital and being told to remain at home. The other 50% of those infected will, given the mildness of their symptoms, treat themselves with febrifuges and continue commuting to work or school. Those who went to the hospital after four days of fever will undergo a PCR test and receive their results the following day, with those infected entering the hospital. The PCR test is implemented here for 50% of those infected. The number of deaths was estimated at half the capture rate of the test, based on the much smaller number of persons estimated to be infected. About 20 days from infection, 20% of the infected will be seriously or critically ill, with people who did not see a doctor in advance also entering the hospital. By 41 days from infection, 0.06% of young people, 0.21% of adults, and 1.79% of the elderly will die. The mildly infected will recover within 27 days from infection, and the seriously ill in the hospital will survive by 49 days after infection, gaining temporary immunity.

The basic parameters of the model are shown in table:model-parameter. The population data and commuting rates were modeled with reference to the Tokyo metropolitan area data from the National Census of the Ministry of Internal Affairs and Communications Bureau of Statistics. The ratio of the elderly used was based roughly on 28% of the population of Japan who were over 65 in 2017. The composition of households with children was based on the infection model of verified existing research, with the same number of commuters (parents) and school attenders (children). The number of trips made out of the house (such as to stores) per day was based on shopping behavior research data. The transmission probability per contact and the respective contact rates were based on the basic reproduction number R0 (2.0-2.5) of COVID-19 and the estimated contact time per day of residents in each location, with the expected values configured equivalent to the base model. The contact rate was changed during the simulation experiment in accordance with each scenario of preventive measures. The rates of seriously ill patients and deaths per generation were set based on reports from the China CDC and the WHO. Mortality rates exceeded 5% in Hubei Province, in particular in Wuhan, but this is thought to be due to sharp increases in mortality because of mass infection with which the medical system was unable to cope. The rate here was set at 0.7% in accordance with other regions and China from February on, after the medical system was organized.

Twenty-seven types of infection prevention measures were planned for this model. To predict their respective effects, they were divided into four categories for experimentation: (1) no preventive measures, (2)-(11) effect of basic preventive measures, (12)-(22) complex effect of basic preventive measures, and (24)-(27) complex effect of contact lowering measures and basic preventive measures.

Tables I shows the parameters set for the measures, and Tables II shows the parameters set for each of these measures.

TABLE I
MODEL PARAMETERS

Model	Prameter
Commuters	400
School-aged children	400
Elderly	320
Commuter ratio	0.5
Transmission probability/contact	0.1
Trips to shops and other places per day	0.5
Train contact rate	0.07
Workplace/school contact rate	0.13
Shop contact rate	0.07
Home contact rate	0.41
Rate of seriously ill patients	0.2
Mortality rate among the young	0.06%
Mortality rate among adults	0.21%
Mortality rate among the elderly	1.79%

IV. SIMULATION EXPERIMENT CONFIGURATION

Using these parameters, 100 simulations for each preventive measure were conducted. The target probability variables changing the random seeds of uniform distribution in each trial were the attributes, address, workplace seating position, school seating position, commuter train boarding position, commercial facility visiting location, and hospital room location of the first person infected.

The two neighboring towns are located in the upper and lower parts of the model, with a total of 1,120 residents. The central area is the commuter train, with the left-hand area representing commercial facilities (event venues), the right-hand area indicating the hospital, and the area the morgue.

V. SIMULATION IMPLEMENTATION RESULTS

The simulation results for each infection prevention measure are shown in Fig. 1 and Fig. **??**. These figures show the number of deaths, number of days elapsed, and median and maximum numbers of seriously ill hospitalized patients per day for each infection prevention measure. The results of 100 trials do not show a specific statistical distribution; their shapes differ widely according to the changed parameters. Therefore, the median was used as a provisional expected value for each measure.

The median number of deaths is about 8 or less, with no significant difference in any case from that when no measures are taken. The median number of days elapsed, which shows the speed of the spread of infection, increases sharply with complex preventive measures. The median number of maximum seriously ill hospitalized patients per day clarifies the reduction due to complex preventive measures and contact reduction measures. Notable reduction by single preventive measures was found in (6) halving trips outside and (11) halving contact overall. The effects of these two preventive measures were investigated in addition to complex preventive measures (flex-time commuting, remote work 50%, and closed schools) in (12)-(17) (reduced frequency of trips outside to shops, etc.) and (18)-(22) (rate of self-isolation after fever onset). Both showed significant effects: Reducing trips outside to shops and other places by half or more from the normal level in addition to complex preventive measures succeeded in reducing seriously ill hospitalized patients and deaths effectively to 0. In addition, similar results were obtained by raising the rate of self-isolation after fever onset to 0.9 or higher (21).

Because the data distribution here does not take a specific shape as in normal distribution, it is not appropriate to evaluate it with weighted averages. Testing was therefore done with the Brunner-Munzel test and Bonferroni correction, deviation testing methods without assumptions that the distribution is the same. Excluding closed schools, remote work 50%, self-isolation rate after fever onset 75%, and contact rate reduction (trains), in comparison with the base (no measures), the result was p0.000037 (Bonferroni correction applied to $p < 0.01$), which was significant. Elsewhere, while the difference was significant, individual corrective measures alone did not show notable effects, making it clear that major effects were derived from the reduction of trips outside to shops and other places and the increased rate of self-isolation after fever onset in addition to complex preventive measures.

Fig. 1 also shows the effects of each measure with median and maximum values. The figures provide confirmation that efficacious effects can be obtained from the use of complex preventive measures combining remote work, closed schools, refraining from trips outside, etc. and that individual measures or combinations of partial measures are not effective for prevention. Elsewhere, it also suggests that other than policies with strong social influence such as closing schools, complex

TABLE II
PARAMETERS OF PREVENTING MEASURES

Measure	1:Base	2:Flex commuting	3:Closed school	4:Remote work.50	5:Self-isolation.75	6:Shops.25	7:Reduced contact, trains	8:Reduced contact, workplace)	9:Reduced contact, shops	10:Reduced contact, home
Remote work	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00
Closed school	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Self-isolation	0.50	0.50	0.50	0.50	0.75	0.50	0.50	0.50	0.50	0.50
Flex commute	-	flex	-	-	-	-	-	-	-	-
Shops/day	0.50	0.50	0.50	0.50	0.50	0.25	0.50	0.50	0.50	0.50
Contact, trains	0.07	0.07	0.07	0.07	0.07	0.07	0.04	0.07	0.07	0.07
Contact, office and school	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.07	0.13	0.13
Contact, shops	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.04	0.07
Contact, home	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.21

Measure	11:Overall reduce contact	12:Complex	13:Complex, shops.45	14:Complex, shops.40	15:Complex, shops.35	16:Complex, shops.30	17:Complex, shops.25	18:Complex, isolation.60	19:Complex, isolation.70	20:Complex, isolation.80
Remote work	0.00	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Closed school	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Self-isolation	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.60	0.70	0.80
Flex commute	-	flex	flex	flex	flex	flex	flex	flex	flex	flex
Shops/day	0.50	0.50	0.45	0.40	0.35	0.30	0.25	0.50	0.50	0.50
Contact, trains	0.04	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Contact, office and school	0.07	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
Contact, shops	0.04	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Contact, home	0.21	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41

Measure	21:Complex, isolation.90	22:Complex, isolation1.0	23:Reduced contact, isolation.75	24:Reduced contact, closed school	25:Reduced contact,flex, remote	26:Reduced c.,flex,remote, school	27:Reduced contact, shops.25
Remote work	0.50	0.50	0.00	0.00	0.50	0.50	0.00
Closed school	1.00	1.00	0.00	1.00	0.00	1.00	0.00
Self-isolation	0.90	1.00	0.75	0.50	0.50	0.50	0.50
Flex commute	flex	flex	flex	flex	flex	flex	flex
Shops/day	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Contact, trains	0.07	0.07	0.04	0.04	0.04	0.04	0.04
Contact, office and school	0.13	0.13	0.07	0.07	0.07	0.07	0.07
Contact, shops	0.07	0.07	0.04	0.04	0.04	0.04	0.04
Contact, home	0.41	0.41	0.21	0.21	0.21	0.21	0.21

measures such as (23) (combining overall contact reduction measures with enhanced self-isolation after fever onset) and (25) (combining flex-time commuting and remote work) can be effective for prevention.

VI. DISCUSSION

Here, I discuss the mechanisms governing the effects of these preventive measures. No major effects resulted from the individual preventive measures (2) through (5) (flex-time commuting, closed schools, remote work, and reinforced self-isolation after fever onset). In addition, no major effects resulted from the individual implementation of the more normal measures of reduced contact (trains, workplaces, schools, shops, and home) in (7) through (10). Elsewhere, for (11), by combining all the contact reduction measures, the number of deaths and of seriously ill hospitalized patients are both reduced by approximately 60%. This enables us to estimate that even one• •slip• •in the places and times where preventive measures are implemented can keep the infection risk high.

Given that there was some effect seen in (6) (restricted trips outside to shops, etc.) even individually, the effects of its combined versions, (13) through (17), were confirmed with the rate changed. Results showed that while the complex preventive measures of (12) (flex-time commuting, remote work, closed schools) alone produced limited effects, the additional combination with the reduced frequency of trips outside showed major effects. This hints that infection is occurring in shops and other places which are not covered by the preventive measures of (12). In particular, the elderly visit shops regularly, as well as parents and children, which means that shops are high-risk locations for infection clusters. Figures on seriously ill hospitalized patients by generation (table:result1 to table:result3) show the following: Compared to the youth and adults, the figures for the elderly are several times higher in all situations. Infection of the elderly in locations such as shops visited by all generations is thought to increase the numbers of seriously ill hospitalized patients and deaths. In addition, for the effective preventive measures, the relative infection speed (base days elapsed/preventive measures days elapsed) is also reduced, and in addition to proper medical care for critically ill patients, tracking of those with direct contact is also easier. This suggests that preventing infection of the elderly will lead to reducing overall numbers of seriously ill hospitalized patients and deaths.

Elsewhere, the increased self-isolation rate after fever onset which did not produce effects in (5) showed significant effects in (18) through (21) when combined with complex preventive measures. This matches the point in the joint report from the WHO and China that the ratio of household-based infection clusters was the highest, suggesting that having infectious patients simply remain at home leads to household-based infection and then infection from family members to the outside. To prevent this, it is extremely important to combine self-isolation with measures such as flex-time commuting, remote work, closed schools, and restricted trips outside. At the moment, given the number of PCR tests and the time limits on confirming testing, it is not possible for fever patients suspected of infection to be taken into hospitals immediately, and as they will inevitably need to self-isolate at home for a period, these complex measures are essential. (In addition, the increased median value for infection with the complex measures in (17) and (21) is due to a high frequency of rapidly subsiding infection cases.)

VII. SUMMARY

This report presents a comparative examination of the efficacy of preventive measures available to ordinary people, corporations, and schools, using an agent-based model of the infection process of COVID-19. The model posits 1,120 virtual resident agents, who commute to work and school and

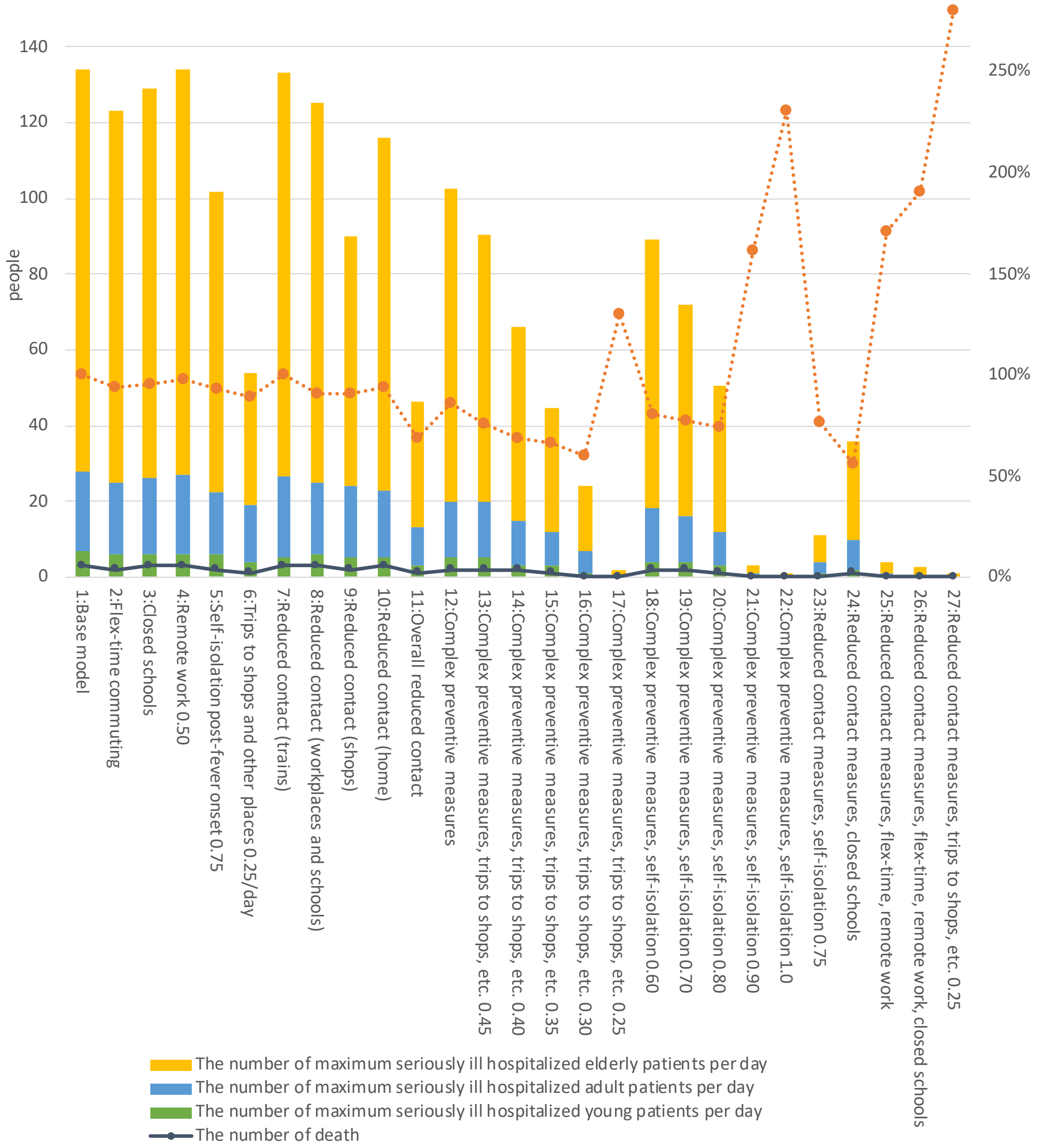

Fig. 1. The median number of death, days elapsed, maximum seriously ill hospitalized patients per day.

visit commercial facilities, imitating exposure to a COVID-19 infection risk. The experiment results clarified that no major effects can be obtained from individual infection prevention measures (flex-time commuting, remote work, closed schools, reduced contact rates, and self-isolation after fever onset) implemented individually or partially in combination. On the contrary, it was confirmed that the implementation of complex measures significantly reduced the mortality rate and number of seriously ill hospitalized patients per day. COVID-19 infection is a process of interaction through contact within a dynamic resident network, without specific distributions for each infection phenomenon. This shows the limits of estimating effects of preventive measures based on examples that have happened to be confirmed. This study evaluated the maximum risks of each type of preventive measure through 100 trial experiments, indicating that the complex use of preventive measures may reduce the maximum risks of infection spread. Reducing the number of seriously ill hospitalized patients is thought to lead to the prevention of the collapse of the medical system and reduce the mortality rate.

This study presents a comparative examination of infection prevention measures. For the greatest currency of information possible, the latest data has been used wherever possible, but new reports are appearing daily, and this paper is limited to the basis of the limited information available as of March 2020. Based on the latest analyses in China, reports indicate that a rapid increase in critically ill patients needing hospitalization increases the mortality rate, because proper medical care can no longer be provided. However, the mortality rate can be rapidly decreased by a quick increase in PCR tests and the number of hospital beds available and by a reinforced tracking system for those with direct contact. This report was unable to address the effects of these medical measures. Examination of the effects of the various event cancellations reported is also called for. The discussion of these issues is an ongoing task.

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