Risk assessment of importation and local transmissions of COVID-19 in South Korea

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Abstract

Background: Despite recent achievements in vaccines, antiviral drugs, and medical infrastructure, the emergence of coronavirus disease (COVID-19) has posed a serious threat to humans worldwide. Most countries are well connected on a global scale, making it nearly impossible to implement perfect and prompt mitigation strategies for COVID-19 outbreaks. In particular, due to the explosive growth of international travel, the diverse networks and complexities of human mobility have become essential factors that give rise to the rapid spread of COVID-19 globally.

Objective: South Korea is one of the countries that experienced the early stage of the COVID-19 pandemic. In the absence of vaccines and treatments, South Korea has implemented and maintained stringent interventions, such as large-scale epidemiological investigations, rapid diagnosis, social distancing, and prompt clinical classification of severe patients with appropriate medical measures. In particular, South Korea has implemented effective airport screenings and quarantine measures. In this study, we aimed to assess the country-specific importation risk of COVID-19 and investigate its impact on the local transmission of COVID-19.

Methods: The country-specific importation risk of COVID-19 in South Korea was assessed. We investigated the relationship among country-specific imported cases, passengers, and the severity of country-specific COVID-19 prevalence from January to October 2020. We assessed the country-specific risk by incorporating country-specific information. A renewal mathematical model was employed, considering both imported and local cases of COVID-19 in South Korea. Furthermore, we estimated the basic and effective reproduction numbers.

Results: The risk of importation from China was the highest between January and February 2020, while that from North America (the United States and Canada) was significantly high from April to October 2020. The R_0 was estimated at 1.87 (95% confidence interval: 1.47, 2.34), with the rate (? =0.07) of the secondary transmission caused by the imported cases. The R_t was estimated in South Korea and in Seoul and Gyeonggi, respectively.

Conclusions: A statistical model accounting for imported and locally transmitted cases was employed to estimate R_0 and R_t. Our results indicated that the prompt implementation of airport screening measures (contact tracing with case isolation and quarantine) successfully reduced local transmission caused by imported cases despite passengers arriving from high-risk countries throughout the year. Moreover, various mitigation interventions, including social distancing and travel restrictions within South Korea, have been effectively implemented to reduce the spread of local cases in South Korea.

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Original Paper

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Keywords: COVID-19 transmission dynamics in South Korea; International travels; Imported and local transmission; Basic reproduction number; Effective reproduction number; Mitigation intervention strategies

Introduction

The coronavirus disease (COVID-19) outbreak has affected human lives worldwide. A novel virus named severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) was identified as the pathogen responsible for the outbreak of COVID-19 [1]. The common symptoms of COVID-19 include fever, dry cough, fatigue, chills, headache, and sore throat. Furthermore, severe symptoms of COVID-19, including high fever, severe cough, and shortness of breath, are often indicative of pneumonia [2]. The first case of COVID-19 was reported in Wuhan, China in early December 2019. On March 11, 2020, the World Health Organization (WHO) declared the outbreak a global pandemic [3]. As of October 31, 2020, a total of 45,551,965 confirmed cases and more than 1,189,306 deaths were reported in 214 countries worldwide. The world has experienced a couple of epidemics caused by coronaviruses (CoVs) from the same family as SARS-CoV-2, such as severe acute respiratory syndrome (SARS) caused by SARS-CoV in 2003 and Middle East respiratory syndrome (MERS) caused by MERS-CoV in 2012, which had a huge impact similar to that of the currently ongoing COVID-19 pandemic. However, the impact of COVID-19 is different in many aspects and is more devastating compared to the other two outbreaks [4-6]. Due to the substantially growing frequency of international travel, the diverse network and complexity of human mobility have become a major reason for the spread of pathogens globally within a short time scale. In particular, the recent new coronavirus variants have been threatening to strengthen border control and lockdown worldwide [7].

In this regard, most researchers have confirmed that COVID-19 has been exported via air travel from mainland China. They have developed many mathematical, statistical, and computational models to analyze air traffic data and estimate the consequent effects. Many researchers have investigated COVID-19 transmission dynamics in various ways. They analyzed the characteristics of pathogen transmission cases in various experiments using elaborate computational models; their findings have enlightened us on how COVID-19 would affect in the future. The volume of international air travel has a significant relationship with the spread of COVID-19 worldwide. A network-driven model for the global spread employed air traffic data to demonstrate and compare the impacts of the H1N1 epidemic in 2009 and the SARS epidemic in 2003 [8]. Furthermore, the risk of MERS-CoV exportation worldwide was evaluated by incorporating seasonal air traffic flows and the time-varying incidence of cases in Middle Eastern countries [9].

Various studies have been conducted on the global spread of COVID-19 during the early stage of the pandemic. One study examined how COVID-19 was imported into Europe by analyzing air traffic data [10]. Another study investigated the risk of transmission of COVID-19 through air flight from four major cities in China (Wuhan, Beijing, Shanghai, and Guangzhou) to the passengers' destination countries [11]. The study identified a risk index of COVID-19 transmission based on the number of travelers to destination countries, weighted by the number of confirmed cases in the departed city reported by the WHO. The importation risk of COVID-19 cases was assessed in Europe from infected areas in China by air travel [12]. The risk before and after the travel ban in Hubei province was compared. Travel restrictions and border control measures have been enforced in China and other countries to limit the spread of the disease [13]. The results of a previous showed that the daily risk of exporting a minimum of one COVID-19 case from mainland China via international travel exceeded 95% on January 13, 2020 [13].

Furthermore, the risk of imported COVID-19 cases was investigated in China by measuring a risk index from inbound international flights in previous studies [14,15]. These studies evaluated policy implications based on the index to adjust international air travel restrictions dynamically. Another study analyzed imported cases of COVID-19 in Taiwan in terms of characteristics, infection source, symptom presentation, and route of identification of imported cases [16]. The study confirmed that the strict enforcement of countermeasures was effective in preventing community transmission. The risks of both importation and exportation of the COVID-19 pandemic have been investigated in a previous study [17]. The study evaluated the risk of importation and exportation of COVID-19 in all airports of 73 countries during the early stage of the pandemic until March 3, 2020.

The diverse network and complexity of human mobility have been identified as essential factors responsible for the rapid spread of COVID-19 globally. Due to the special situation between South Korea and North Korea, international air flights are the most frequent way of direct access to South Korea. In particular, due to a large number of international travelers from China, South Korea experienced the early stage of the COVID-19 pandemic. In the absence of vaccines and treatments, South Korea has implemented and maintained stringent interventions such as large-scale epidemiological investigations, rapid diagnosis, case isolation, contact tracing, quarantine, and social distancing. Despite the overall dramatic decrease in international flights, there is still a constant inflow of flights from high-risk countries. Therefore, the risk of COVID-19 in South Korea must be assessed.

In this study, we investigated the impact of international travel on the local transmission dynamics of COVID-19 in South Korea. First, we identified the relationship between the number of international travelers and country-specific confirmed cases of COVID-19. We computed the country-specific importation risk of COVID-19, accounting for the number of travelers entering South Korea; the number of confirmed cases in the originating countries; and the population size of the originating countries. Second, statistical modeling was employed to capture the impact of secondary transmission caused by both imported and local cases of COVID-19 and explore the basic reproduction number (R_0) and the effective reproduction number (R_t). Finally, we assessed the impact of imported cases on the local transmission of COVID-19.

Methods

Epidemiological data

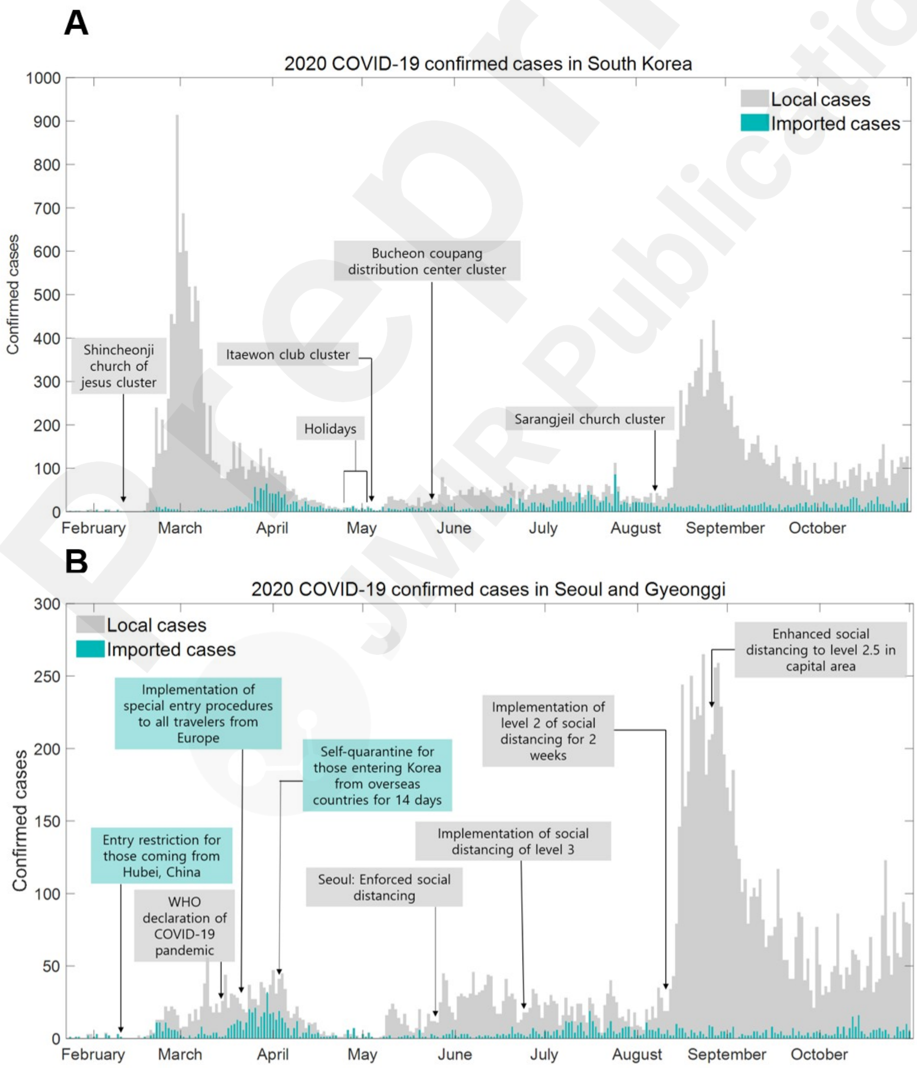
We analyzed country-specific epidemiological data on COVID-19 cases and the international travel volume in South Korea from January to October 2020. First, data on the number of confirmed COVID-19 cases in South Korea were extracted from the Korea Disease Control and Prevention Agency (available to the public) [18]. The epidemiological data included the dates of confirmation, dates of symptom onset, and transmission classification (local transmission/imported cases) [19]. Second, data on the monthly number of entry passengers entering South Korea in 2019–2020 was gathered from Incheon International Airport [20]. Data on the number of passengers who arrived at Incheon International Airport was available to the public. Third, data on the number of confirmed cases of COVID-19 from the countries of origin were collected from the WHO situation report [21] and their population size is obtained from [22]. The country-specific data are presented in Table S1 and Figures S1–S5.

Epidemiological characteristics of COVID-19 transmission dynamics in South Korea

We have presented the epidemic curves of local and imported cases in South Korea in Figure 1A and in Seoul and Gyeonggi in Figure 1B. Most COVID-19 cases occurred in March 2020 (due to the explosive outbreak in Daegu and Gyeongbuk), and the number of cases in Seoul and Gyeonggi increased steadily from May 2020, leading to a larger outbreak in September 2020. Figure 1B shows the epidemic curve in Seoul and Gyeonggi along with the timeline of screening and quarantine interventions (green box) and social distancing interventions (gray box). The list of selected interventions is presented in Table S2. The COVID-19 transmission dynamics in South Korea showed spatial heterogeneity. There were two major hotspots. First, the early outbreak was focused in the Daegu and Gyeongbuk areas from February to April due to the Shincheonji church-related clusters, as shown in Figure 1A and reported previously [23,24]. Second, the late outbreak was focused in the Seoul and Gyeonggi areas in September and November 2020, which were triggered by the Sarangjeil church-related gathering on August 15, 2020, as shown in Figure 1A.

The timeline of the administrative measures implemented in South Korea is shown in Figure 1B and Table S2. The Korean government, Seoul, and Gyeonggi implemented administrative countermeasures in response to the COVID-19 outbreak, including guidelines for entry restrictions followed by the 2-week self-quarantine guidelines from a different period combined with social distancing interventions.

Figure 1 Epidemic curve of imported cases and local cases in South Korea. **A.** Daily number of imported and local cases of COVID-19 in South Korea. **B**. Daily number of imported and local cases in Seoul and Gyeonggi. Gray bars and green bars represent local cases and imported cases, respectively.



Risk of importation of COVID-19

We aimed to calculate the country-specific importation risk of COVID-19 based on the number of international travelers, confirmed cases in the originating countries, and the population size of the originating countries. The countries were grouped as Europe (the United Kingdom (UK), Germany, and France); China, Asia except for China (Asia (except China)), and North America (the United States and Canada). Country-specific importation risk is defined as a function of three factors, population, the number of confirmed cases of COVID-19, and passengers entering to Korea [25,26]. The risk importation entering from the country in month was derived as follows:

$$Risk_{c,t} = \frac{I_{c,t}}{pop_c} T_{c,t}, (1)$$

where t is the month from January 2020 to October 2020 ($t=1,2,\cdots,10$) and c is a group of countries ($c=$¿ {China, Asia (except China), Europe, North America}). $I_{c,t}$ stands for the monthly confirmed cases of COVID-19 in a month t and an originating country c. The population-adjusted density of infectious travelers was obtained by $I_{c,t}$ dividing its population size pop_c of country c. $T_{c,t}$ represents the number of passengers traveling from country c in month t. The normalized risk for country c in month t was as follows:

$$Normalized\,Risk_{c,t}(\%) = \frac{Risk_{c,t}}{Max(Risk_{c,t})} \times 100, (2)$$

where $Max(Risk_{c,t})$ indicates the maximum of the $Risk_{c,t}$ for month t and country c. Moreover, we obtained a correlation between the monthly number of passengers and cases of COVID-19. We calculated the monthly Pearson’s correlation coefficients between the number of passengers and the number of COVID-19 cases corresponding to the different countries including Japan, Vietnam, Philippine, US, China, Thailand, Taiwan, Malaysia, Singapore, Germany, France, Canada, UK. The Pearson’s correlation coefficients are higher than 0.7 from April 2020, indicating that the number of passengers had a linear relationship with the number of COVID-19 cases in 2020. Overall, this implied that prompt country-specific surveillance should be implemented for a more cautious screening process that may be applied to passengers from higher-risk countries. The reason of the high correlation was owing to two major countries—China was the highest risk country in the early stage of the pandemic, while the United States was the highest risk country in the later stage of the pandemic.

Estimation of reproduction numbers

In this section, a renewal equation was employed to estimate the R_0. The R_0 is defined as the average number of susceptible individuals infected by a single primary case. Previous studies on COVID-19 estimated the R_0 to be 2–3 [26-28]. In this study, we have categorized the total cases into locally transmitted (local cases) and imported cases. The total incidence of COVID-19 at time *t*, denoted by $i(t)$, is the sum of local cases ($i_L(t)$) and imported cases ($i_o(t)$), that is, $i(t)=i_o(t)+i_L(t)$. The renewal equation for the transmission dynamics of COVID-19 is defined as follows [31-32]:

$$E(i_L(t)) = R_0 \sum_{t=1}^{tn} (i_L(t-\tau) + \alpha i_o(t-\tau)) f_\tau, 0 \le \alpha \le 1, (3)$$

where f_τ is the probability distribution of the serial interval in τ, and α is the relative contribution caused by the imported cases to the secondary disease transmission ($0 \le \alpha \le 1$) [27,33]. A serial interval is the time interval from illness onset in a primary case (infector) to that in a second case (infectee) [28]. The serial interval was assumed according to the gamma distribution with a mean of 4.8 days and a standard deviation of 2.3 days [33,34]. The likelihood function, assuming that the daily counts follow a Poisson distribution, is defined as:

$$L(R_0; i_L(t), i_o(t)) = \sum_{t=1}^{t_n} \frac{e^{-E(i_L(t))} E(i_{L(t)})^{i_L(t)}}{i_L(t)!}, (4)$$

where t_n is the final time. We estimated the R_0 using the early confirmed cases from January

10 to February 25, 2020 using Equations (3) and (4). Here, α is the relative contribution caused by imported cases to the secondary disease transmission [27,33]. In Seoul and Gyeonggi, there were secondary confirmed cases of importation until April 2020, and there were very few secondary confirmed cases due to stringent interventions such as screening and the self-quarantine policy from April to June 2020. Forty-eight secondary cases related to imported cases were reported until June 2020, and the parameter α was calculated based on the total confirmed cases by April and June 2020. As of April 2020, the value of α was 7.57%, while that of α was reduced to 3.63% in June 2020.

The R_0 is relevant only in a largely susceptible population. Therefore, we also introduced the time-dependent reproduction number R_t, calculated as the ratio of the number of new locally infected cases at time t and all infected individuals at time t. The details of the R_t computation can be found elsewhere [32,35]. The effective reproduction number was estimated on sliding windows of width W days, which was assumed to be a constant value over the time window (W-day average of R_t).

$$R_t = \frac{\sum_{s=t-W+1}^{t} i_L(s)}{\sum_{s=t-W+1}^{t} \sum_{u=1}^{t} \left(i_L(t-u) + \alpha i_o(t-u) \right) f_u}$$

If $W=1$, then the R_t is derived as follows:

$$R_t = \frac{i_L(t)}{\sum_{u=1}^{t} \left(i_L(t-u) + \alpha i_o(t-u) \right) f_u}$$

Results

Relation between the number of passengers and the imported cases was explored and the normalized country-specific risk was obtained. Among four groups of countries, China had a high risk of importation until February 2020. Afterward, North America showed a high risk of importation. The number of imported cases in Korea had a high correlation with the normalized risk, acquiring Spearman's correlation coefficient to be 0.82. The R_0 was estimated at 1.87 (95% confidence interval: 1.47, 2.34), with the rate (α ¿0.07) in Seoul and Gyeonggi. R_0 was varied according to α, to be between 1.83 And 3.94 In South Korea. The R_t in South Korea and in Seoul and Gyeonggi were shown and interpreted along with the control interventions, respectively.

Imported and local cases of COVID-19 in South Korea

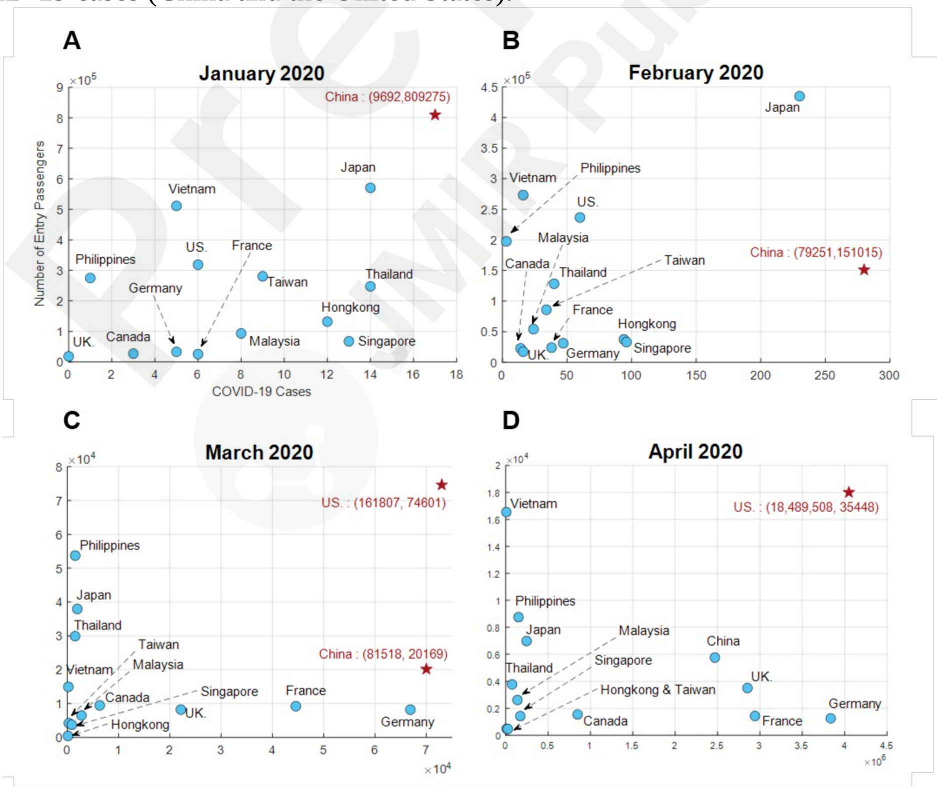
Figure S1 illustrates a summary of the epidemiological data on COVID-19 cases in South Korea. The top panels of Figure S1A show the overall characteristics of the confirmed cases from February to October 2020. The leftmost panel shows the ratio of COVID-19 cases by region—43% in the Seoul and Gyeonggi areas, 33% in the Daegu and Gyeongbuk areas, and 24% in the rest of South Korea. The second panel shows the ratio of imported cases (14%) to local cases (86%). The third panel shows the number of confirmed cases in Seoul and Gyeonggi and the ratios of imported cases (10%) to local cases (90%). The rightmost panel shows that 31% imported cases were reported in Seoul and Gyeonggi. Seoul and Gyeonggi are the regions with the most inflow of foreigners in South Korea as major international airports are located here (Incheon and Gimpo International Airports).

Figure S1B shows the monthly proportion of imported cases from five continents and the total proportion of imported cases (top left panel). A list of country-specific imported cases is given in Table S1. The number of imported cases from China was large during January and April 2020, while that from North America and Europe increased until April 2020. However, the number of imported cases from Asia increased rapidly from May to October 2020; Asia (50.6%), North America (28.1%), and Europe (17.8%) accounting for most of the cumulative imported cases.

Relation between the number of passengers and imported cases of COVID-19

The importation risk implies that the county with more COVID-19 cases and more travelers entering South Korea has a higher risk of importation. Figure 2 shows the relationship between the number of passengers entering South Korea in 2020 and the monthly confirmed cases of COVID-19 between January and April in 2020. After February 2020, the number of Chinese passengers rapidly decreased due to the emerging outbreak of COVID-19 in China, as shown in Figures 2A and 2B. The number of confirmed cases and the number of passengers entering Korea from the US increased from March to October 2020 shown in Figure S2. This indicated that the number of passengers was dramatically reduced since the COVID-19 pandemic began owing to travel bans and restrictions (See Table S2). Next, the number of international travelers who arrived in South Korea in 2020 was compared with that in 2019 (Figure S3). The number of country-specific confirmed cases and passengers per month from the top 13 countries from January to October 2020 are shown in Figures S4 and S5, respectively. The number of cases in China was reduced dramatically from March 2020 (Figure S4A), while the number of cases in the United States, the UK, France, Germany, Canada, and Malaysia continued to increase until October 2020 (Figures S4H–M). However, the number of passengers was greatly reduced, regardless of the country, as shown in Figure S5.

Figure 2. Relationship between the monthly number of passengers entering South Korea and COVID-19 cases at originating countries from January to April 2020. The red star represents the substantially large number of COVID-19 cases (China and the United States).



Importation risk of COVID-19

We presented the risk of country-specific importation in Figure 3 and Table 2. Between

January and February 2020, the risk of importation from China was the highest among other countries, while that from North America (the United States and Canada) showed a significantly high risk of importation from April to October 2020. The number of imported cases was highly correlated with the normalized risk by calculating Spearman's correlation coefficient and Kendall's correlation coefficient to be 0.82 and 0.64, respectively.

Figure 3. Normalized risk. The bar graph shows the country-specific risk of importation in the top 13 countries from January to October 2020 in South Korea.

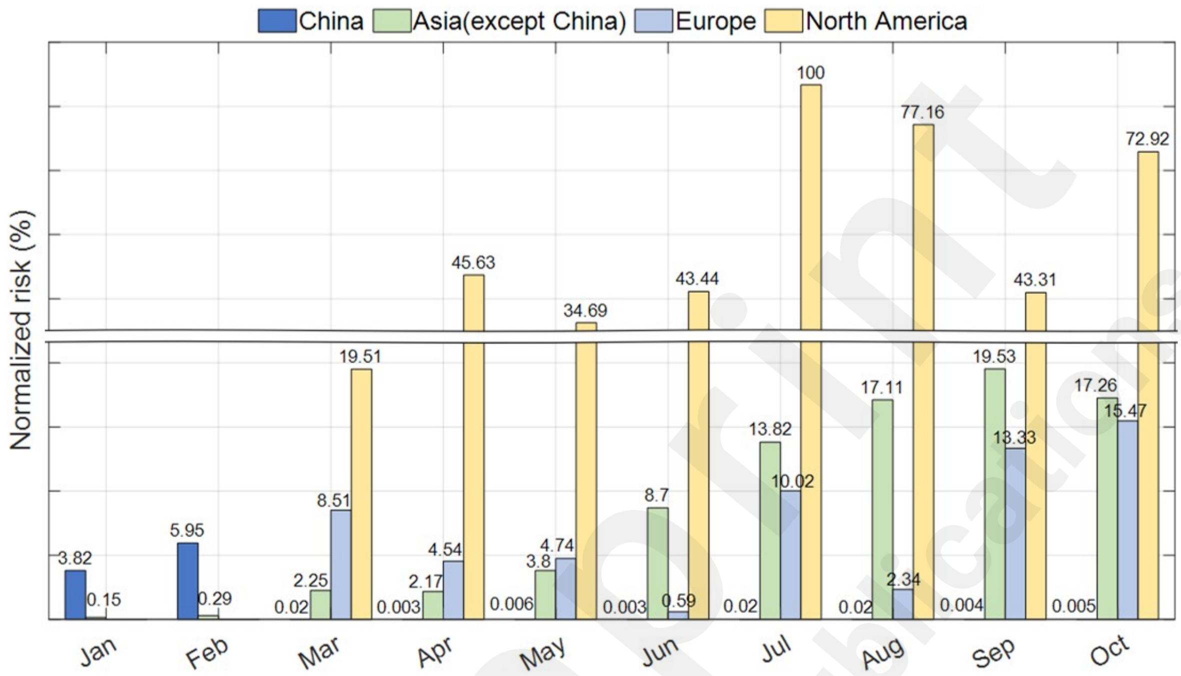
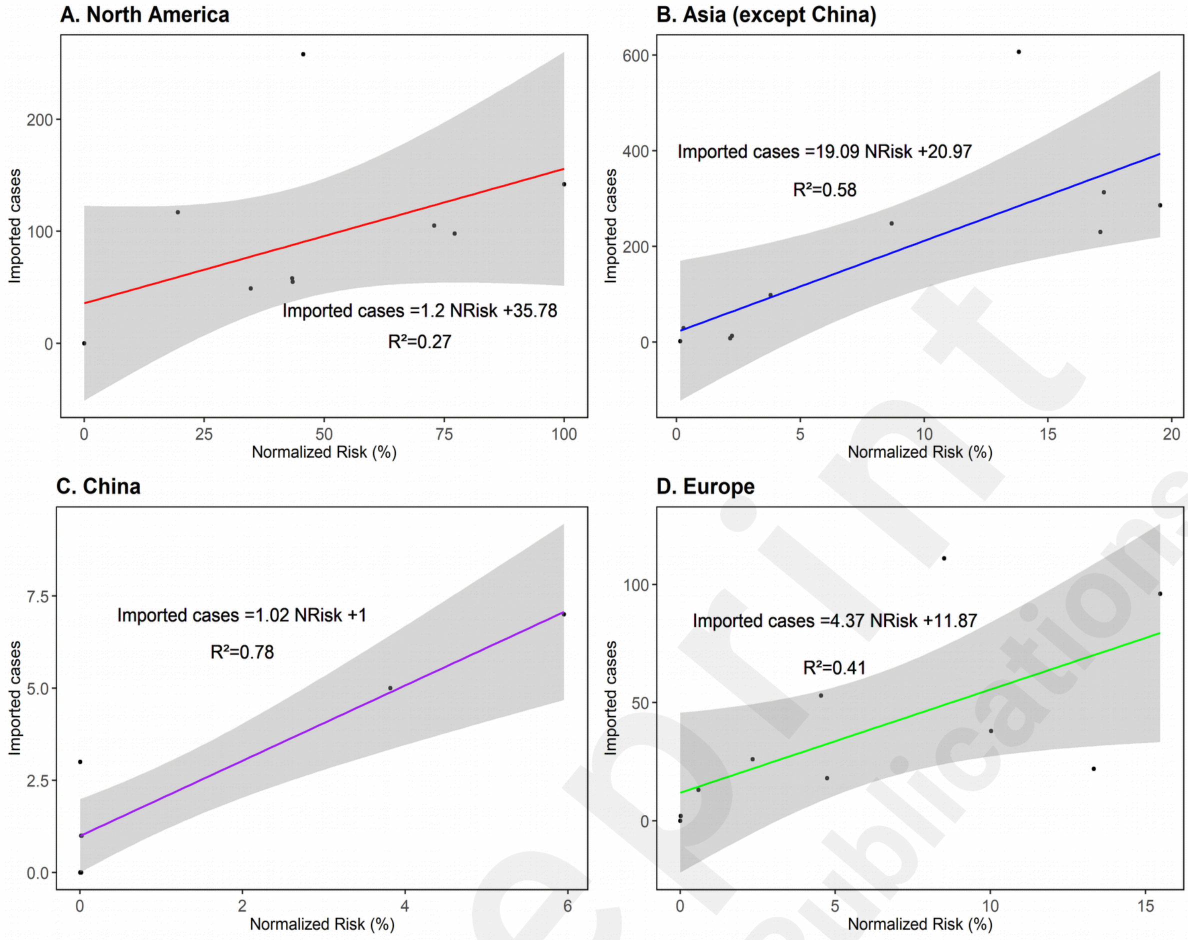


Figure 4 showed the results of regression analysis between the country-specific risk and the number of imported cases according to the four different countries. The estimated values using the regression analysis were summarized in Table S3. All countries had a positive relationship between the imported cases and the risk of importation because estimates of slopes were positive. The linear regression models were well fitted especially to China ($R^2=0.78$). The Asia (except China) was the most affected country with respect to the risk of importation. It is clear that the imported cases entering from Asia (except China) can be much more increasing if the risk importation of Asia (except China) is elevated.

Figure 4. Regression Analysis between the imported cases in South Korea and Normalized Risk (%). The dots indicate the number of imported cases in South Korea and solid lines represent the fitted linear regression. NRisk indicates the Normalized Risk.



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We varied α from 0 to 1 and estimated the R_0 for the early COVID-19 outbreak in Seoul and Gyeonggi based on COVID-19 confirmed cases from January 10 to February 25, 2020 and that in South Korea bases on COVID-19 confirmed cases from February 1 to February 19 in Table 1. Figure 5 shows the comparison between the COVID-19 data and estimated cases (Figure 4A) and cumulative local cases (Figure 4B). The corrected Akaike information criterion was calculated at 159.08 and the Bayesian information criterion was 160.84. Table 1 illustrates the estimation of R_0 with varying α. The estimated R_0 was 1.87 (95% CI: 1.47–2.34) with $\alpha=0.07$ and 1.49 (95% CI: 1.17, 1.87) with $\alpha=1.0$. This indicated that the value of R_0 decreased with the increasing α since there was no secondary infection from imported cases $(\alpha=1)$.

The R_t was calculated for $\alpha=0.07$ shown in Figure 6. The daily epidemic curves of imported (green) and local (gray) cases and the R_t values (blue curve) in the Seoul and Gyeonggi regions. On March 11, 2020, when the WHO declared a pandemic situation, the R_t value fell below 1. At the beginning of the holiday season in early May 2020, the value again increased rapidly. In addition, there was a large outbreak in August and September 2020 due to a public gathering from all over South Korea on August 15, 2020. We conducted the sensitivity analysis for R_t according to the different time windows and α, which is shown in Figures S6A and S6B. Additionally, the R_t in South Korea from April to October 2020 is shown in Figures S6C and S6D.

Table 1. Estimation of R_0 by α

	Korea		Seoul and Gyeonggi	
α	R_0	95% CI*	R_0	95% CI*
0.00	3.94	(2.18–6.04)	1.89	(1.49–2.38)
0.07	3.76	(2.11–5.75)	1.87	(1.47–2.34)
0.10	3.63	(2.05–5.58)	1.85	(1.46–2.33)
0.30	2.98	(1.71–4.66)	1.76	(1.38–2.21)
0.50	2.53	(1.47–4.00)	1.67	(1.31–2.10)
0.70	2.19	(1.28–3.50)	1.59	(1.25–2.00)
1.00	1.83	(1.08–2.94)	1.49	(1.17–1.87)

95% CI* was calculated from profile likelihood [36].

Figure 5. Comparison between estimated cases and observed cases of COVID-19 in Seoul and Gyeonggi using R_0 when $\alpha=0.07$. **A**. Daily local cases in Seoul and Gyeonggi. **B.** Cumulative local cases in Seoul/Gyeonggi. The red bar shows the estimated cases, while the blue bar shows the observed COVID-19 cases. in the Seoul and Gyeonggi regions.

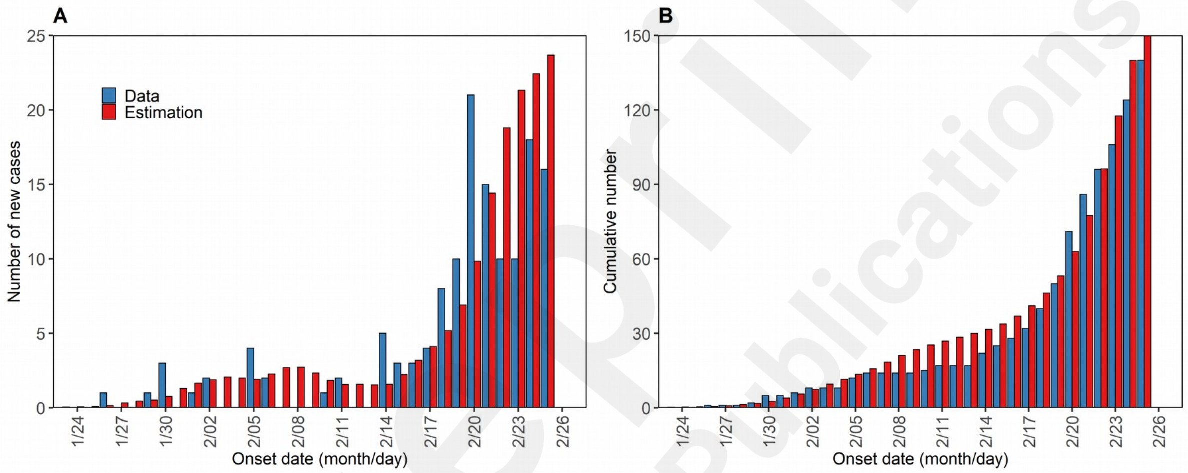
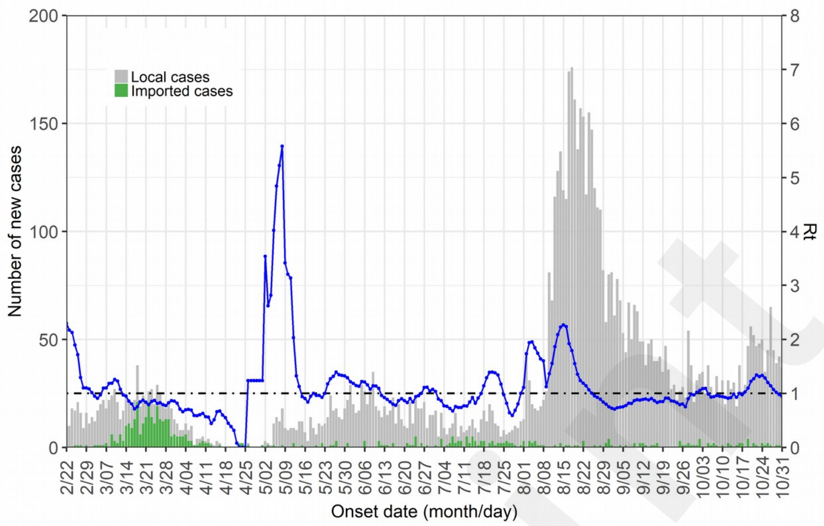


Figure 6. Local and imported cases and R_t in Seoul and Gyeonggi. The daily epidemic curves of imported (green) and local (gray) cases were shown. The blue curve shows the value of R_t when $\alpha=0.07$ and the black horizontal line denotes $R_t=1$.



Discussion

In the present study, we analyzed country-specific epidemiological data and data on passengers entering South Korea from January to October 2020. First, the correlation between the number of passengers and the COVID-19 cases by country was calculated. A country with more confirmed cases showed a higher risk of importation. Second, the country-specific risk was highly correlated with the number of imported cases by country (Spearman's correlation coefficient: 0.82); China had the highest importation risk of COVID-19 in the early stage (January and February 2020), while the North America (United States and Canada) showed the high importation risk from April to October 2020. Third, for the early stage of COVID-19, the R_0 was estimated at 1.87 (95% CI: 1.47–2.34), which was similar to the R_0 of COVID-19 of approximately 2–3 in Wuhan, China [28-30]. Finally, we estimated the R_t by employing the renewal equation, accounting for the effects of the control interventions

The world is experiencing a COVID-19 pandemic; however, mainland China and South Korea experienced a steep rise in the number of COVID-19 confirmed cases in the early stage of the pandemic [3, 34]. It appears that the two governments' respective reactions to the novel virus resulted in a successful reduction in infection rates; however, the cost burden that the two countries had to bare was quite different. China implemented the lockdown in Hubei province and strict border control measures against higher-risk countries [37,38]. In China, active measures driven by the central government to retard the progress of epidemic diseases appear to be effective for impeding the spread of COVID-19; however, Chinese people had to pay burdensome costs during the initial outbreak of COVID-19. South Korea used strict social distancing measures and self-quarantine without restricting borders. However, South Korea expanded the volume of testing and promptly traced the infection process of confirmed cases [34, 39].

There were potential risk factors that could have lead to a larger outbreak of COVID-19 in South Korea. First, negative serial intervals indicated pre-symptomatic transmissions, which describe the potential risk of transmission from asymptomatic cases. A 12.7% serial intervals were negative in South Korea (199 pairs among 1,567 symptomatic pairs), which could lead to large outbreaks as secondary transmission before the symptoms cannot be prevented [39,40]. Second, the R_0 was estimated at 1.49 in Seoul and Gyeonggi, indicating that an endemic or epidemic might be possible. Third, the number of imported cases increased substantially from April 2020, although the passenger volume has been rapidly decreasing due to the increase in COVID-19 cases. However, a large outbreak of COVID-19 caused by imported cases did not occur because the policy of testing arriving passengers from other countries and isolating them for a minimum of 2 weeks implemented on April 1, 2020 reduced the risk of the spread of COVID-19.

The present study has several limitations. First, this study relied on confirmed cases in South Korea. However, there were a substantial number of asymptomatic infections as 12.5% negative serial intervals were observed [40], which represents the pre-symptomatic transmission [34,39]. Thus, we did not consider secondary transmission caused by imported and local cases. Second, we analyzed the impact of imported cases on the local transmission of COVID-19 and found that the impact of imported cases had decreased since the strict implementation of airport screening and quarantine measures from April 2020 [41,42] (See S2 Table). Therefore, the potential risk of infection from imported cases was regarded as a less important factor. However, the reason for the small outbreak from imported cases was due to the strengthened screening inspection and self-quarantine measures for those entering South Korea, implemented on April 1, 2020. This means that secondary transmission by imported cases can play a critical role in COVID-19 transmission. Finally, the risk was estimated by month as monthly passenger volume data were available. If the daily data are given, the risk by country can be computed daily or weekly. However, we observed a significantly different risk of importation of COVID-19 from overseas countries.

Despite these limitations, we investigated the risk of importation of COVID-19 using country-specific epidemiological data and passenger volume. By combining social distancing, screening, and self-quarantine for all travelers entering South Korea, the mitigation of COVID-19 transmission caused by imported cases in South Korea was highly successful. These efforts, accompanied by identification of the source of infection, and strengthened quarantine measures for travelers from overseas countries should be continued. Therefore, it is urgent to assess the risk of importation and maintain an effective surveillance system for COVID-19 in South Korea.

Control interventions were strictly implemented to prevent the spread of COVID-19 in South Korea since the first case was confirmed on January 20, 2020 in South Korea. The COVID-19 outbreak in Korea has been successfully suppressed without the strict lockdowns. First, the Korean government has constructed a rapid testing and diagnosis system [39,43]. Previous studies have shown that most cases have been confirmed within a week after illness onset [42,43]. Moreover, drive-through screening centers (“Drive-Thru”) were initiated on February 23, 2020, in Daegu, South Korea [44]. This system contributed to the rapid diagnosis and further testing of the suspected cases. The entire testing procedure of Drive-Thru takes only about 10 min, and it is helpful to diagnose early infection in cases with mild symptoms or asymptomatic cases. Second, the widespread epidemiological investigation of contact tracing was conducted in infected as well as suspected cases [39]. Social distancing strategies and wearing masks have been recommended since February 2020. The effect of social distancing has been analyzed to mitigate the spread of COVID-19 cases [39,45,46]. Third, the Korean government introduced a “special entry procedure, which was applied to all passengers from mainland China from February 4, 2020 to control imported cases. Subsequently, all passengers from overseas countries were quarantined for 14 days after April 1, 2020. Combined control interventions, including social distancing efforts, appear to have succeeded in preventing the spread of COVID-19.

Since the severity of COVID-19 prevalence and health policies differ in most countries, a country-specific surveillance system would be more efficient than the uniform screening and surveillance policy for every country. Another notable feature of South Korean immigration is that the number of international travel hubs is limiting and the passenger traffic can be effectively monitored. This, in turn, helps in diagnosing and tracing imported cases without imposing a strict lockdown. It is important to estimate the country-specific risk importation by identifying which countries have high-risk importation in order to prevent recurrent outbreaks due to the importation and exportation. It would be helpful to access a finer level of information to estimate the effective reproduction number as the risk indicator of importation and local transmission. Therefore, our framework can also be applied to countries having similar environments with immigration policies. Furthermore, risk assessment of imported cases for the countries being a part of a union with abolished border control such as the Schengen zone or Central America-4 Free Mobility Agreement might be challenging.

Conclusions

Data on international passengers entering South Korea, the severity of COVID-19 prevalence in originating countries, and country-specific imported cases were analyzed to compute the risk of importation of COVID-19 in South Korea. China was a high-risk country of importation in the early stage until March 2020, while the United States and Canada showed a high risk of importation after April 2020. Moreover, statistical model accounting was employed to estimate the R_0 and R_t using epidemiological data on imported and locally transmitted cases. Our results highlighted that rapid diagnosis and prompt implementation of case isolation and quarantine were effective in preventing secondary infections caused by imported cases through the continuous inflow of passengers traveling from high-risk countries. Therefore, a combined mitigation intervention such as social distancing, a rapid diagnosis system, and movement restriction should be implemented to reduce the spread of local and imported cases in South Korea.

Table 2. Normalized risk of importation in South Korea by country using data on population size, number of COVID-19 cases and number of passengers from January to October in 2020

Country	Population	Month	Cases	Passengers	Normalized risk of importation (%)
Europe	214921407	1	11	77183	0.002
		2	115	72133	0.02
		3	141116	25656	8.51
		4	453720	6182	4.54
		5	584312	3450	4.74
		6	634734	4963	0.59
		7	684781	6224	10.02
		8	833071	6701	2.34
		9	1233958	4595	13.33
		10	2715743	4441	15.47
Asia(except China)	3032800000	1	168	5535607	0.15
		2	1254	1397128	0.29
		3	70717	190649	2.25
		4	224609	57968	2.17
		5	558836	40838	3.8
		6	1105224	47219	8.7
		7	1786777	46420	13.82
		8	2709219	37908	17.11
		9	3410902	34362	19.53
		10	3009642	34419	17.26
China	1399620000	1	9701	1089779	3.82
		2	79285	236911	5.95
		3	81824	24381	0.02

		4	83287	6242	0.003
		5	85012	9479	0.006
		6	85674	11120	0.003
		7	88423	15323	0.02
		8	90839	19579	0.02
		9	91480	18690	0.004
		10	92402	16193	0.005
North America	365968433	1	9	346090	0.004
		2	74	259247	0.02
		3	168124	84074	19.51
		4	1061615	36987	45.63
		5	1805819	33757	34.69
		6	2640886	37676	43.44
		7	4504036	38869	100
		8	5982879	37783	77.16
		9	7110608	27809	43.31
		10	8989268	28109	72.92

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Ethical Considerations

The data are presented in Table S1. The datasets were fully anonymized and did not include any personally identifiable information. Thus, ethical approval was not required for the analysis.

Conflicts of Interest

None declared

Abbreviations

COVID-19: coronavirus disease
WHO: World Health Organization

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Supplementary Files

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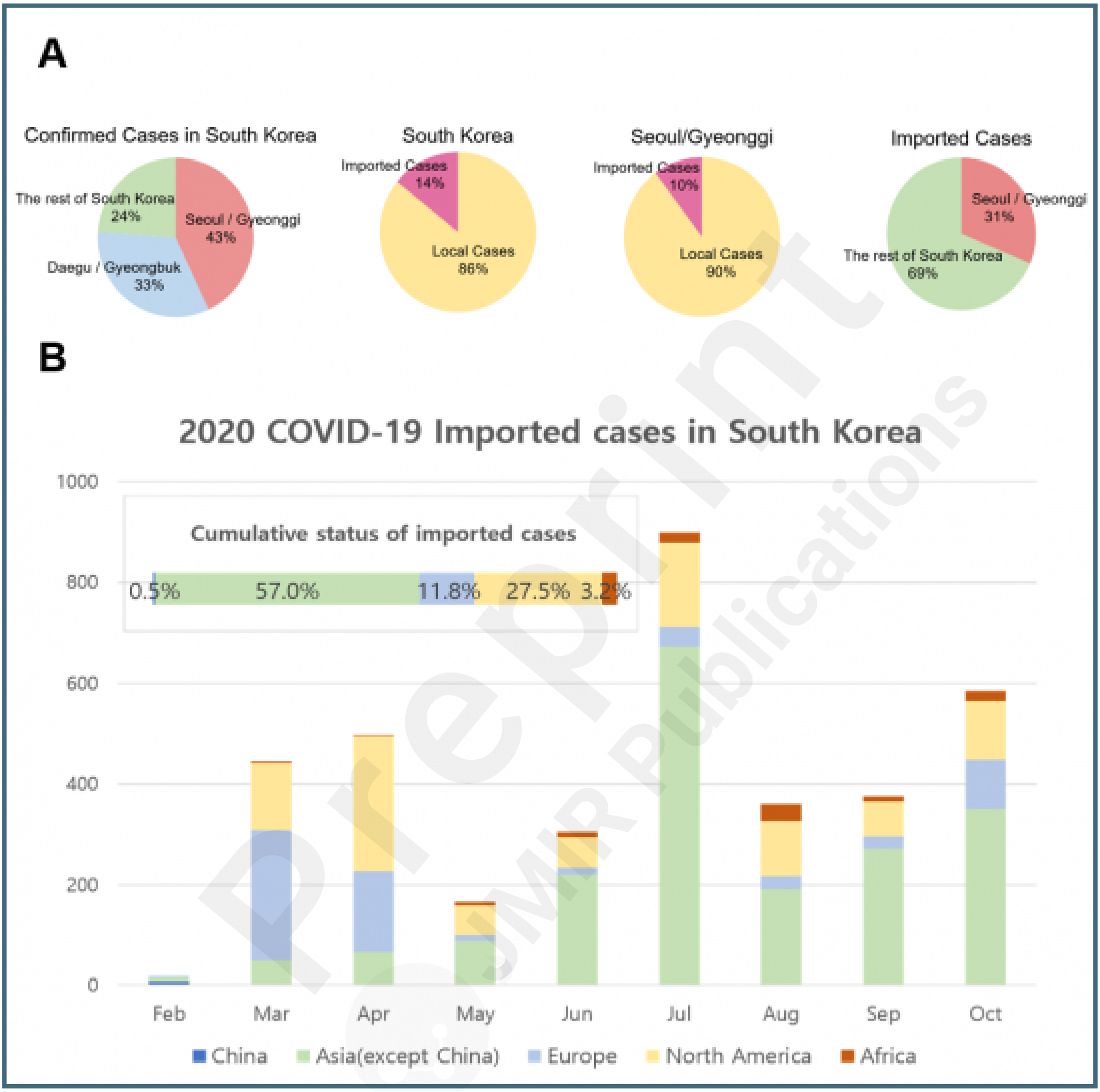
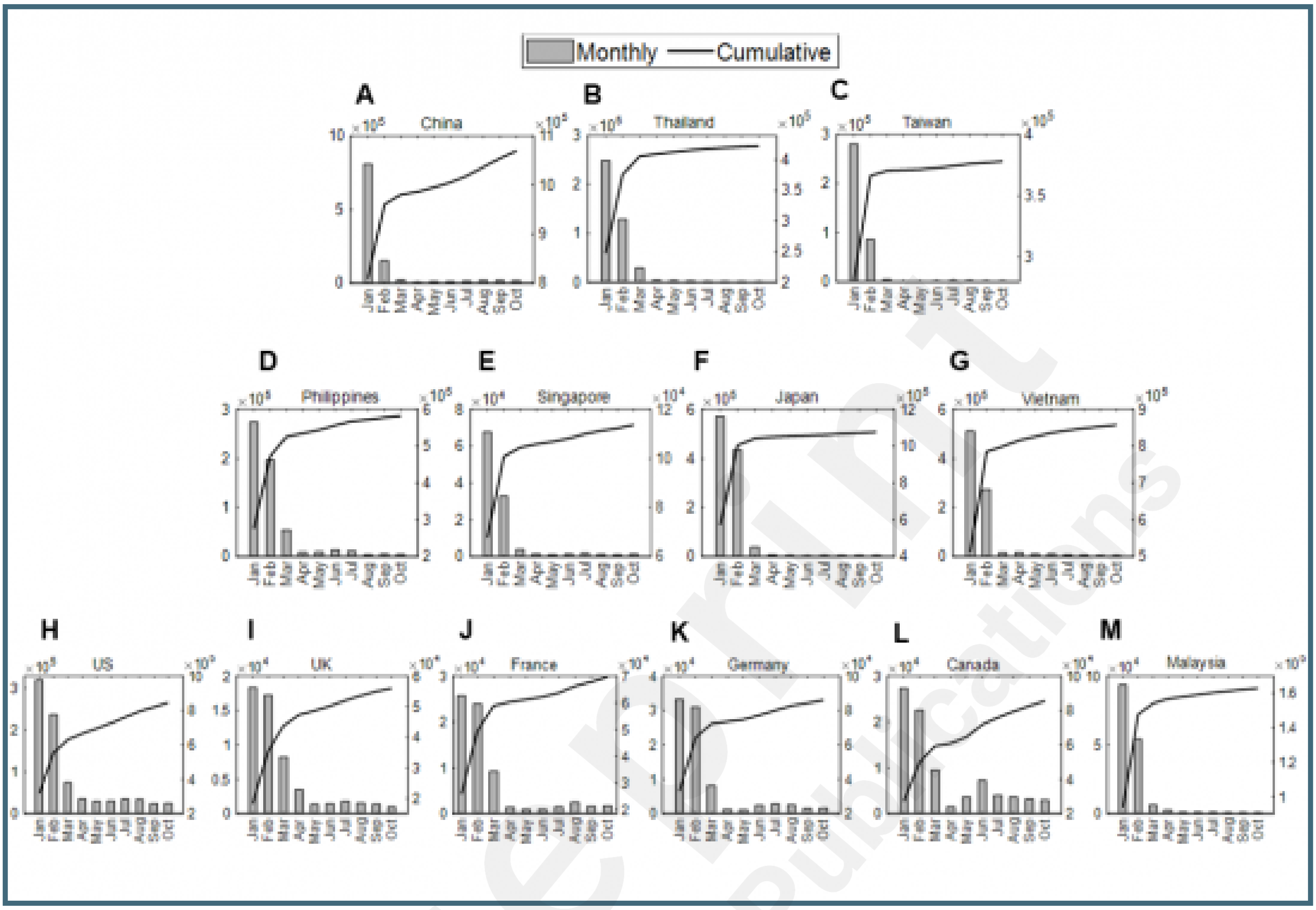
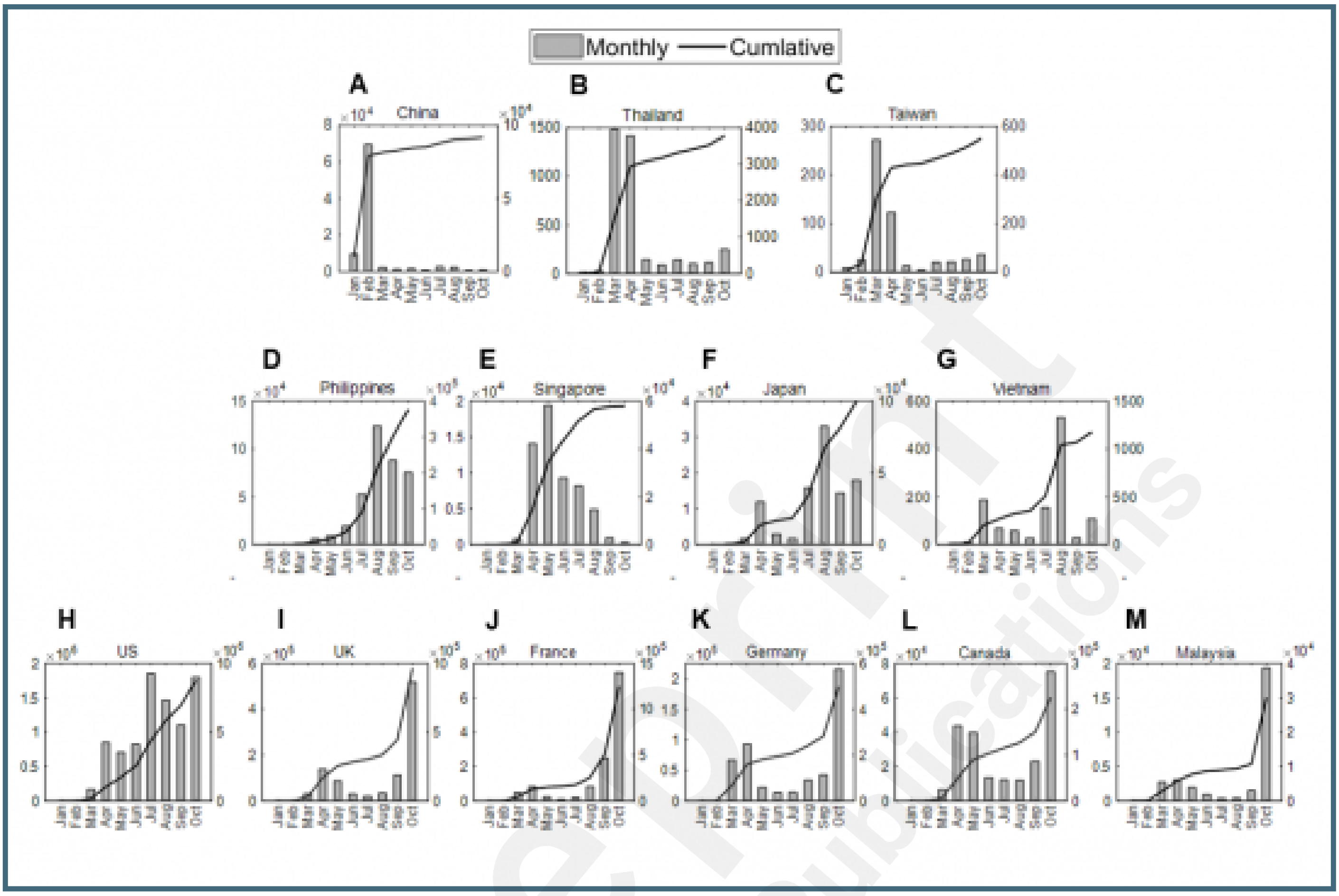

A
Confirmed Cases in South Korea
The rest of South Korea 24%
Seoul / Gyeonggi 43%
Daegu / Gyeongbuk 33%
South Korea
Imported Cases 14%
Local Cases 86%
Seoul/Gyeonggi
Imported Cases 10%
Local Cases 90%
Imported Cases
Seoul / Gyeonggi 31%
The rest of South Korea 69%
B
2020 COVID-19 Imported cases in South Korea
Cumulative status of imported cases
0.5% 57.0% 11.8% 27.5% 3.2%
1000
800
600
400
200
0
Feb Mar Apr May Jun Jul Aug Sep Oct
China Asia(except China) Europe North America Africa

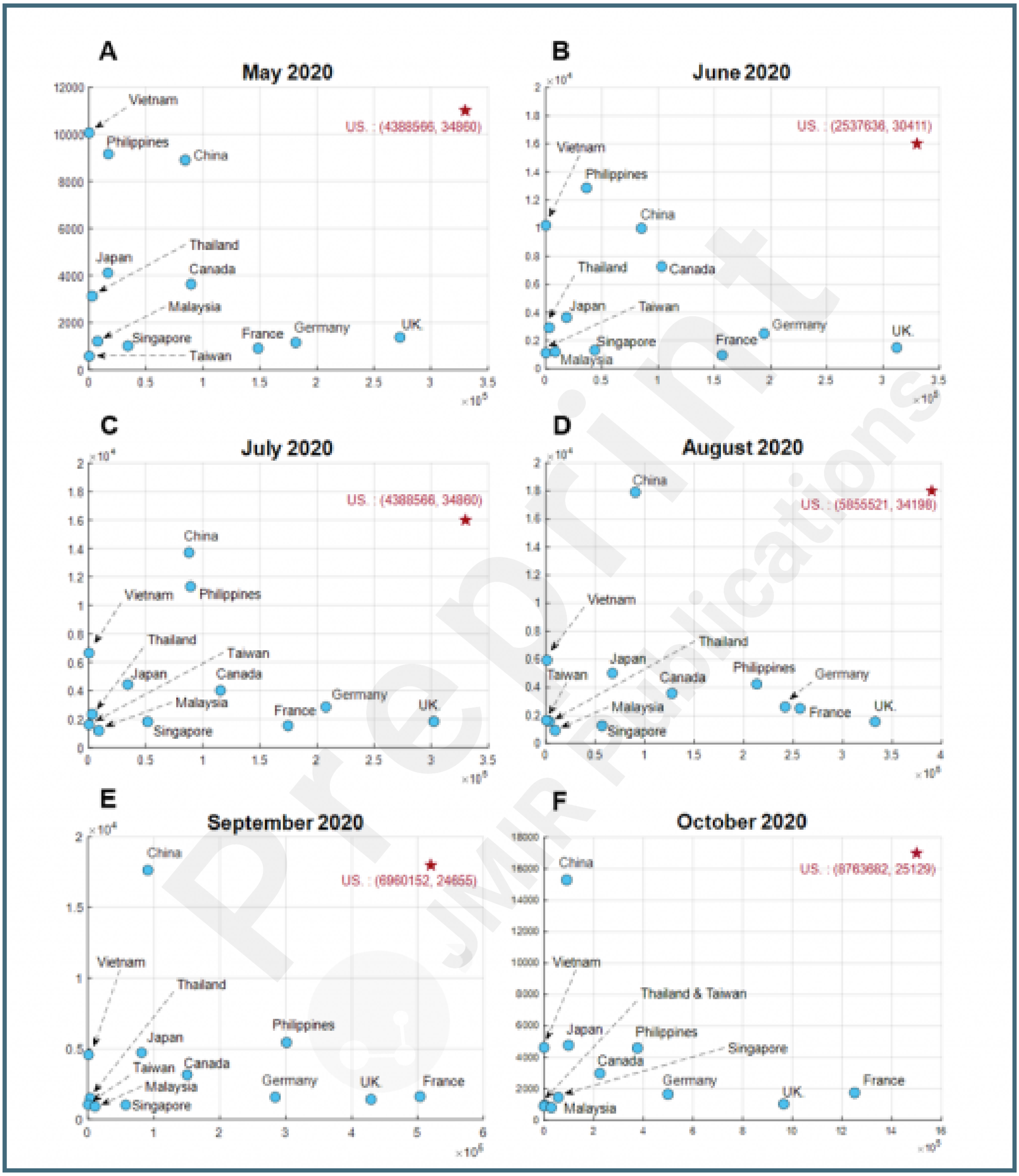
Untitled.


Monthly
Cumulative
A
China
B
Thailand
C
Taiwan
D
Philippines
E
Singapore
F
Japan
G
Vietnam
H
US
I
UK
J
France
K
Germany
L
Canada
M
Malaysia

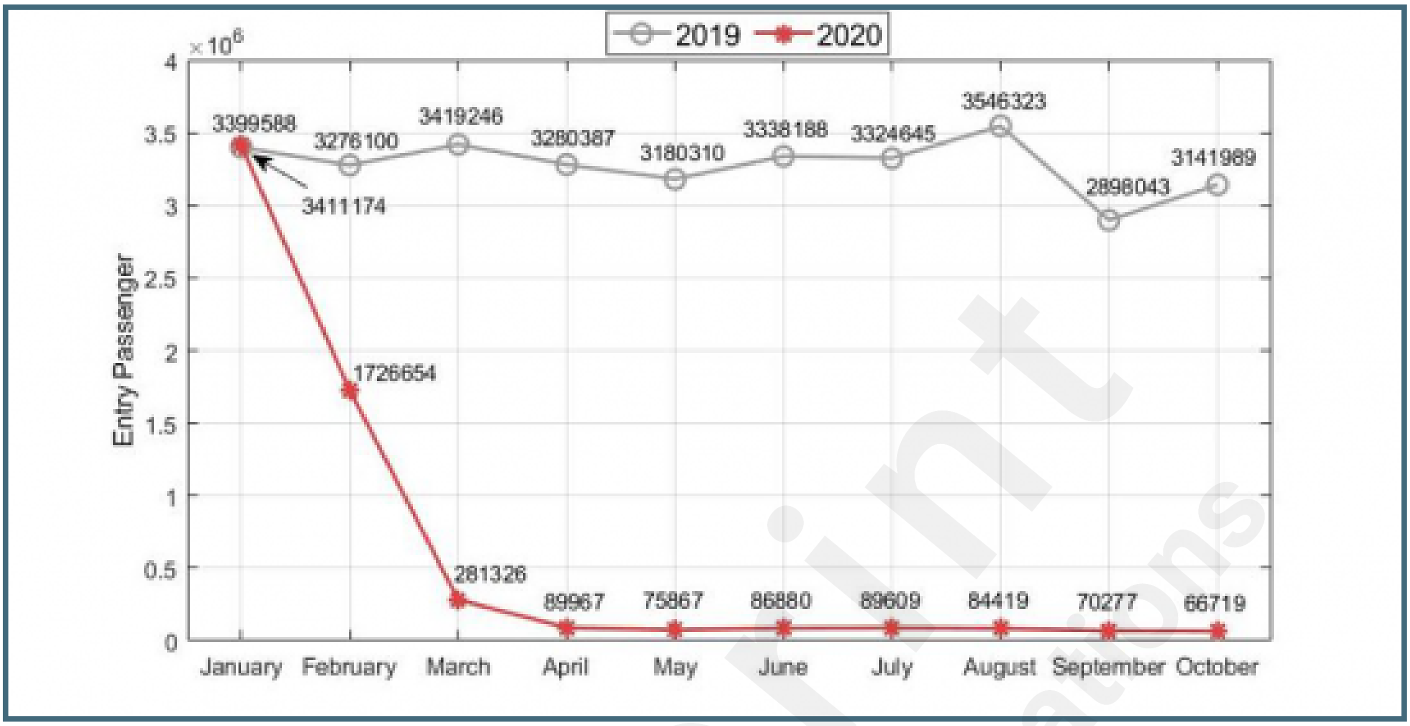
Untitled.


Monthly
Cumlative
A
China
B
Thailand
C
Taiwan
D
Philippines
E
Singapore
F
Japan
G
Vietnam
H
US
I
UK
J
France
K
Germany
L
Canada
M
Malaysia

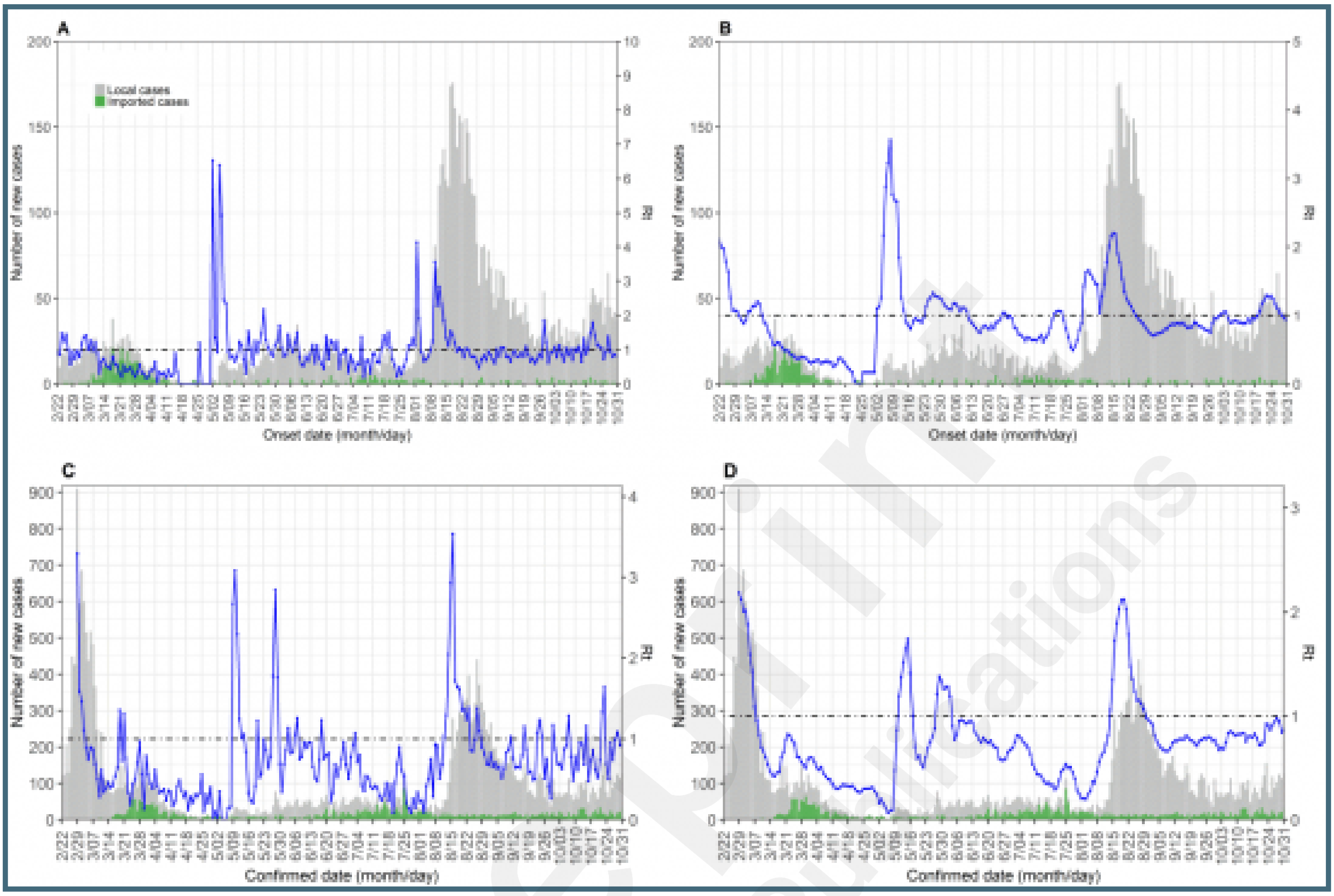
Untitled.


A
May 2020
US. : (4388566, 34860)
Vietnam
Philippines
China
Japan
Thailand
Canada
Malaysia
Singapore
Taiwan
France
Germany
UK.
B
June 2020
US. : (2537636, 30411)
Vietnam
Philippines
China
Thailand
Canada
Japan
Taiwan
Singapore
Malaysia
France
Germany
UK.
C
July 2020
US. : (4388566, 34860)
China
Philippines
Vietnam
Thailand
Taiwan
Japan
Canada
Malaysia
Singapore
France
Germany
UK.
D
August 2020
US. : (5855521, 34198)
China
Vietnam
Thailand
Japan
Taiwan
Canada
Philippines
Germany
Malaysia
Singapore
France
UK.
E
September 2020
US. : (6960152, 24655)
China
Vietnam
Thailand
Japan
Taiwan
Canada
Malaysia
Singapore
Philippines
Germany
UK.
France
F
October 2020
US. : (8763682, 25129)
China
Vietnam
Thailand & Taiwan
Japan
Philippines
Singapore
Canada
Germany
UK.
France
Malaysia

Untitled.


2019
2020
×10^6
4
3.5
3
2.5
2
1.5
1
0.5
0
Entry Passenger
3399588
3276100
3419246
3280387
3180310
3338188
3324645
3546323
2898043
3141989
3411174
1726654
281326
89967
75867
86880
89609
84419
70277
66719
January
February
March
April
May
June
July
August
September
October

Untitled.


A
Local cases
Imported cases
Number of new cases
Rt
Onset date (month/day)
B
Number of new cases
Rt
Onset date (month/day)
C
Number of new cases
Rt
Confirmed date (month/day)
D
Number of new cases
Rt
Confirmed date (month/day)

Figures

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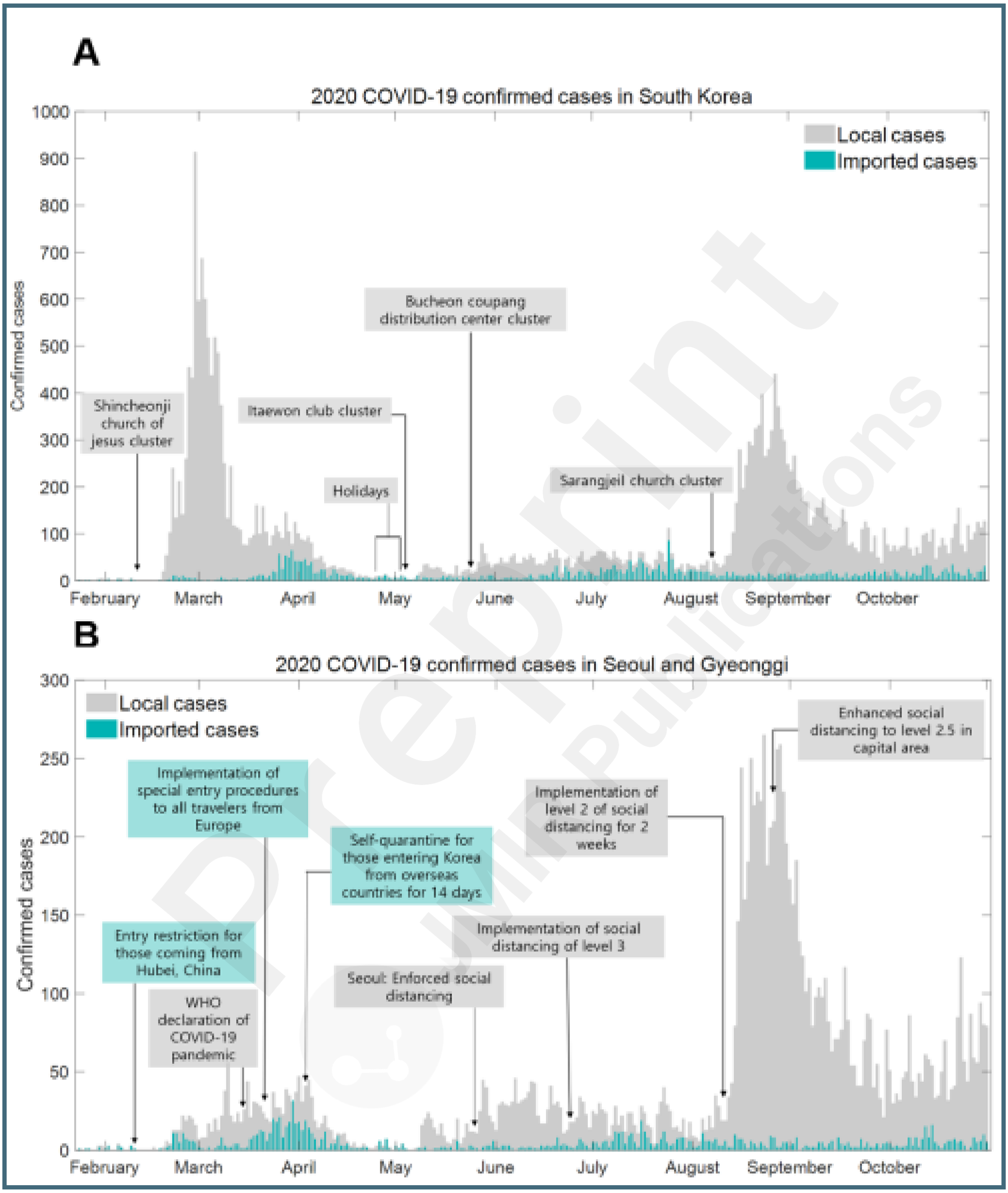
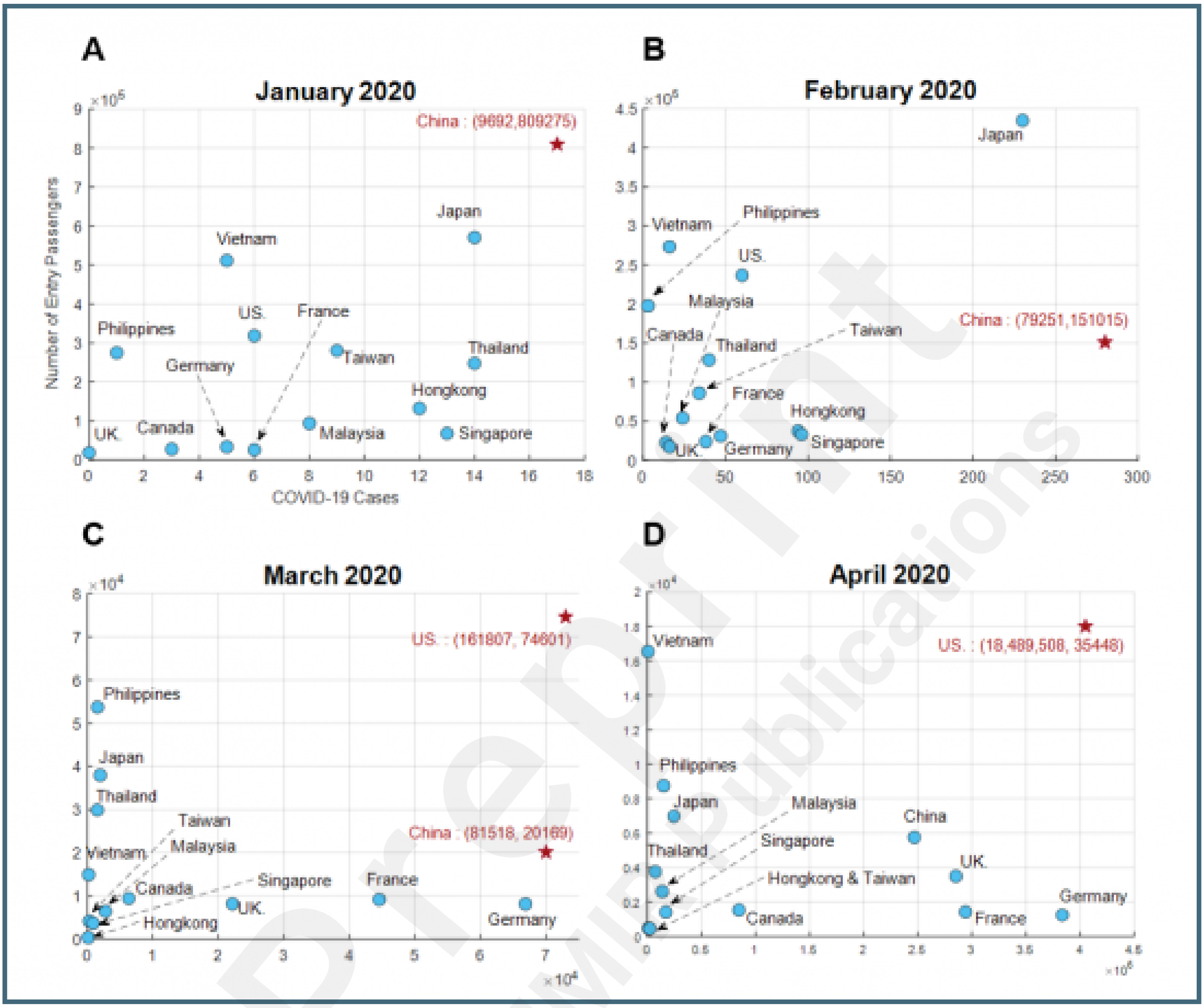
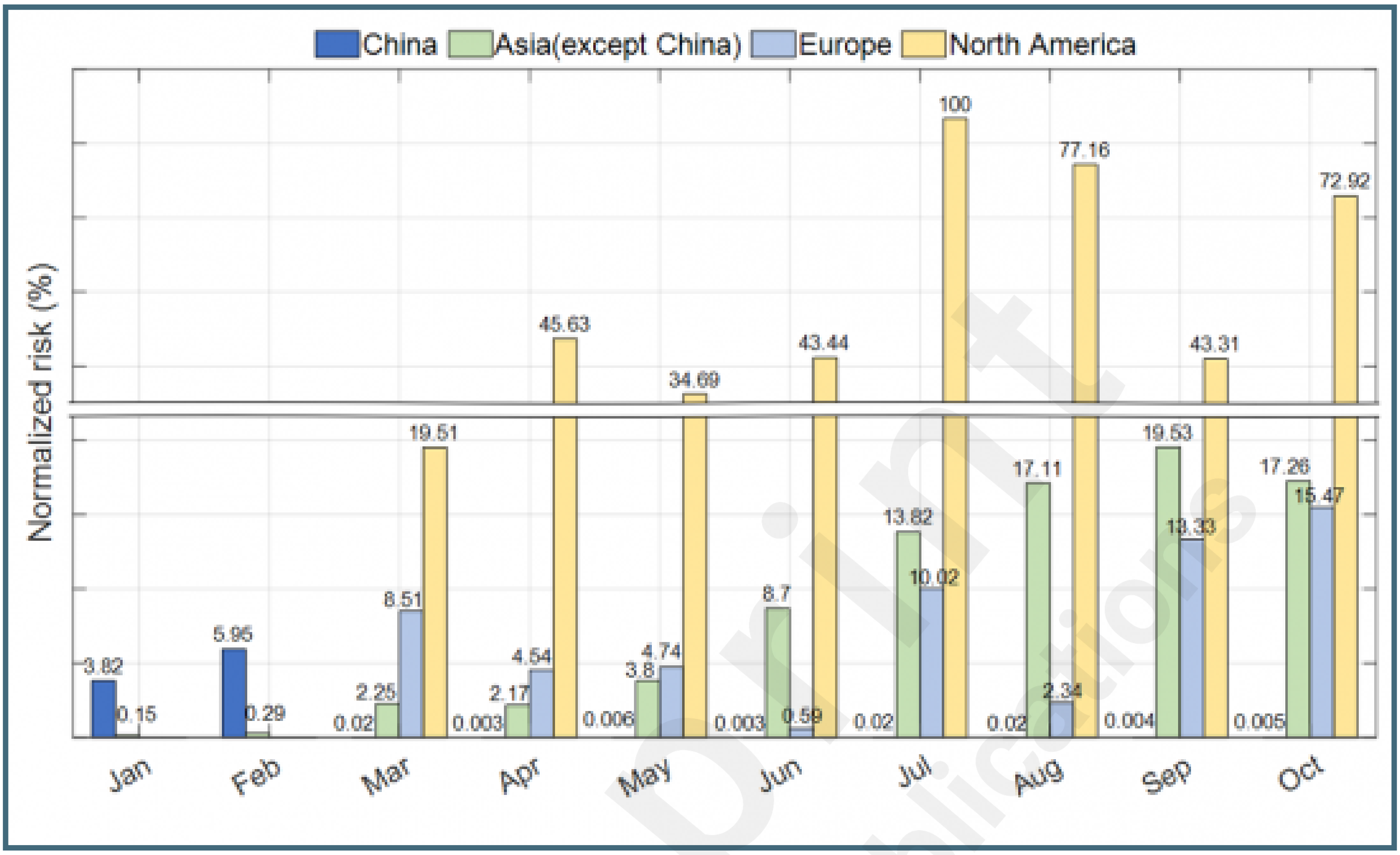

A
2020 COVID-19 confirmed cases in South Korea
Local cases
Imported cases
Confirmed cases
1000
900
800
700
600
500
400
300
200
100
0
Shincheonji church of jesus cluster
Itaewon club cluster
Holidays
Bucheon coupang distribution center cluster
Sarangjeil church cluster
February
March
April
May
June
July
August
September
October
B
2020 COVID-19 confirmed cases in Seoul and Gyeonggi
Local cases
Imported cases
Confirmed cases
300
250
200
150
100
50
0
Implementation of special entry procedures to all travelers from Europe
Self-quarantine for those entering Korea from overseas countries for 14 days
Implementation of level 2 of social distancing for 2 weeks
Enhanced social distancing to level 2.5 in capital area
Entry restriction for those coming from Hubei, China
Implementation of social distancing of level 3
Seoul: Enforced social distancing
WHO declaration of COVID-19 pandemic
February
March
April
May
June
July
August
September
October

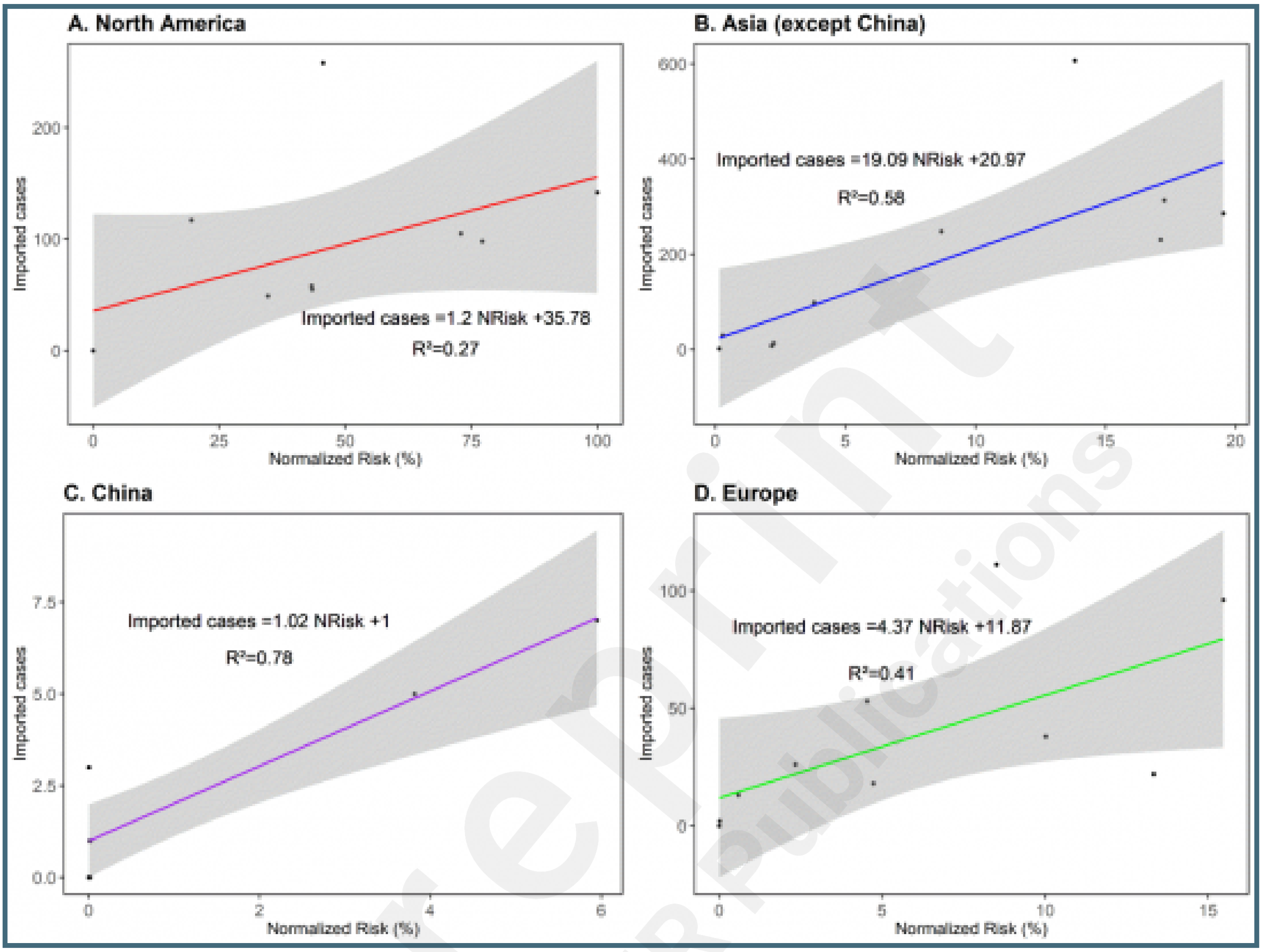
Untitled.


A
January 2020
China : (9692,809275)
Japan
Vietnam
US.
France
Philippines
Taiwan
Thailand
Germany
Hongkong
UK.
Canada
Malaysia
Singapore
Number of Entry Passengers
COVID-19 Cases
B
February 2020
Japan
Vietnam
Philippines
US.
Malaysia
Canada
Thailand
Taiwan
China : (79251,151015)
France
Hongkong
UK.
Germany
Singapore
C
March 2020
US. : (161807, 74601)
Philippines
Japan
Thailand
Taiwan
Vietnam
Malaysia
China : (81518, 20169)
Canada
Singapore
France
UK.
Hongkong
Germany
D
April 2020
Vietnam
US. : (18,489,508, 35448)
Philippines
Japan
Malaysia
China
Thailand
Singapore
UK.
Hongkong & Taiwan
Germany
Canada
France

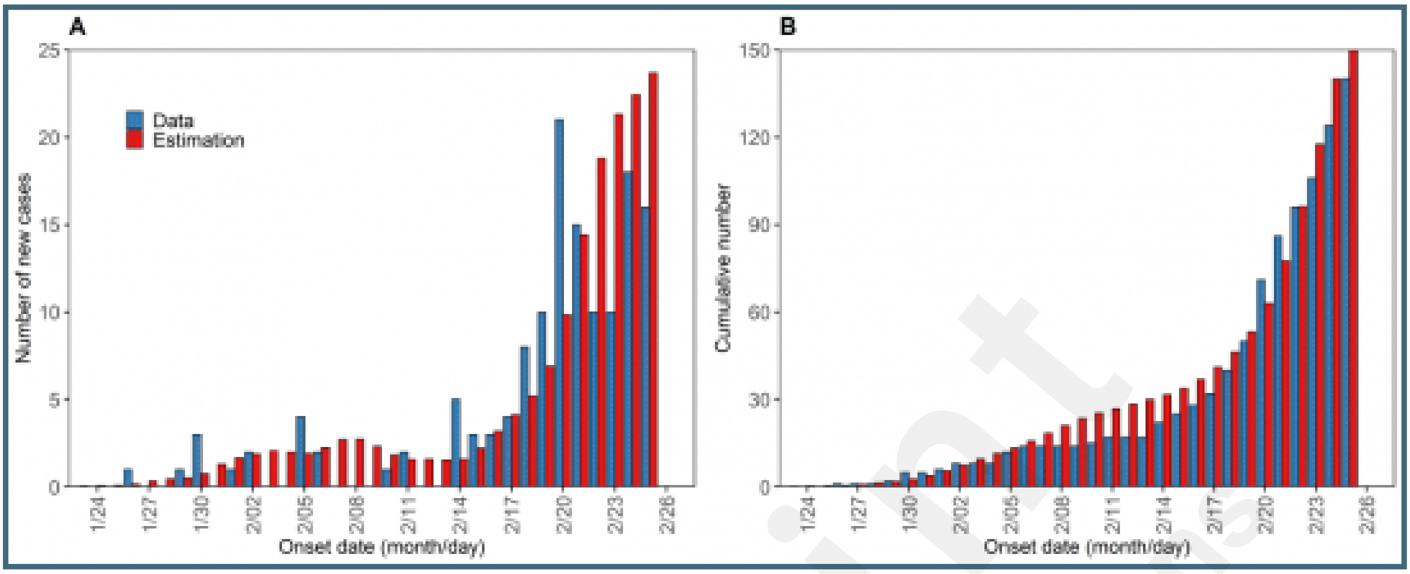
Untitled.


China
Asia(except China)
Europe
North America
Normalized risk (%)
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
3.82
0.15
5.96
0.29
0.02
2.25
8.51
19.51
0.003
2.17
4.54
45.63
0.006
3.8
4.74
34.69
0.003
8.7
0.59
43.44
0.02
13.82
10.02
100
0.02
17.11
2.34
77.16
0.004
19.53
13.33
43.31
0.005
17.26
15.47
72.92

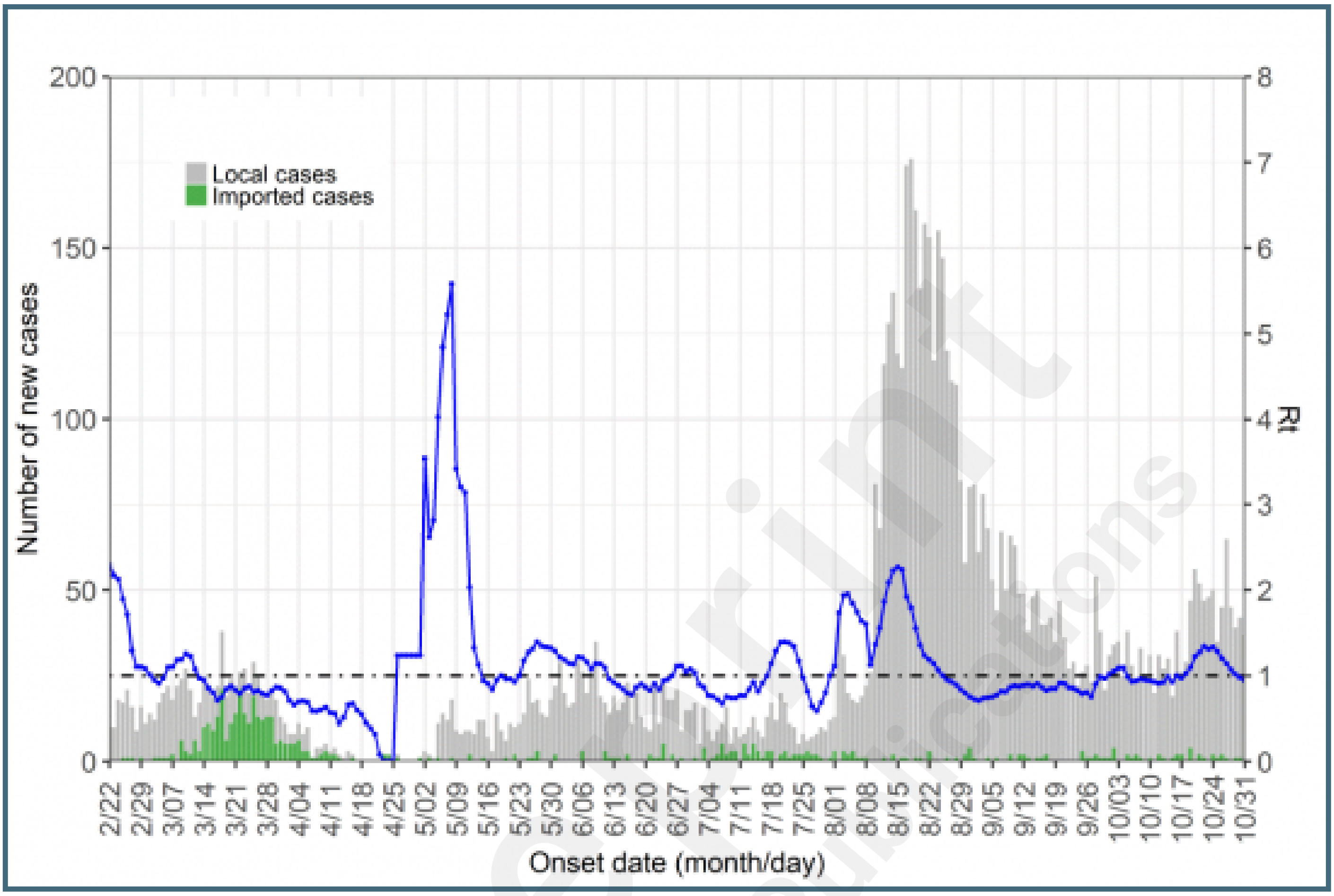
Untitled.


A. North America
Imported cases =1.2 NRisk +35.78
R²=0.27
Imported cases
Normalized Risk (%)
B. Asia (except China)
Imported cases =19.09 NRisk +20.97
R²=0.58
Imported cases
Normalized Risk (%)
C. China
Imported cases =1.02 NRisk +1
R²=0.78
Imported cases
Normalized Risk (%)
D. Europe
Imported cases =4.37 NRisk +11.87
R²=0.41
Imported cases
Normalized Risk (%)

Untitled.


A
B
Data
Estimation
Number of new cases
Cumulative number
Onset date (month/day)
Onset date (month/day)
1/24
1/27
1/30
2/02
2/05
2/08
2/11
2/14
2/17
2/20
2/23
2/26
0
5
10
15
20
25
30
60
90
120
150

Untitled.


Local cases
Imported cases
Number of new cases
Rt
Onset date (month/day)
0
50
100
150
200
0
1
2
3
4
5
6
7
8
2/22
2/29
3/07
3/14
3/21
3/28
4/04
4/11
4/18
4/25
5/02
5/09
5/16
5/23
5/30
6/06
6/13
6/20
6/27
7/04
7/11
7/18
7/25
8/01
8/08
8/15
8/22
8/29
9/05
9/12
9/19
9/26
10/03
10/10
10/17
10/24
10/31

Multimedia Appendixes

Untitled.
URL: http://asset.jmir.pub/assets/b78091cd6f6a5c622cbcb4f0da4eccd0.docx