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The Role of Contact Tracing and Testing in Korea's Response to COVID-19

한국의 코로나19 대응에서 접촉자 추적 및 검사의 역할

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Abstract

South Korea's success in control the spread of COVID-19 has been remarkable among countries that adopted suppression strategy. South Korea's extensive tracing and large-scale testing had drawn attention as a success factor. Therefore, the objectives of this study are to suggest a general criterion for tracing and testing based on South Korea's experience, and to propose a new framework to assess tracing and testing. In addition, we investigated the relationships between tracing and testing and the spread of COVID-19.

South Korea expanded its testing capabilities to overcome its lack of tracing capabilities with group tracing and preemptive testing and open testing. According to the SEQIR model developed based on South Korea's strategies, COVID-19 cases were divided into 4 types (Confirmed in quarantine, Source known, Source unknown, and Unidentified), and case types can be useful indicators to assess tracing and testing.

As a result of analyzing the relationship between tracing and testing and the spread of COVID-19 using these case type indicators, timely quarantine of contacts through tracing and testing had the preventive effect on the COVID-19 incidence over 2 weeks. On the other hand, increasing in the untraced proportion was found to increase the risk of COVID-19 outbreaks.

In conclusion, large–scale tracing and testing in South Korea played a role in suppressing the occurrence of untraced cases. South Korea could suppress COVID–19 transmission by maintaining a high traced proportion (above 60%) using group tracing and preemptive testing strategy which is a complementary strategy to contact tracing. In addition, as the effect of early quarantine of contacts through contact tracing disappeared after 2 weeks, efforts are needed to maintain maximum tracing and testing capabilities, and early implementation of group tracing and preemptive testing strategy is required to complementary to contact tracing.

Keywords : COVID–19, Contact tracing, Testing, Group tracing, Preemptive testing, Quarantine, Source of infection

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Introduction

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1.1. Study background

Contact tracing and testing played a key role to control spread of COVID-19 worldwide. In general, extensive contact tracing and large-scale testing have been described as effective measures to control COVID-19. A study analyzing the effects of each NPI (non-pharmaceutical intervention) in 173 regions around the world reported that R_t could be reduced by 9% if the ratio of test to case increased 10 times (*1*). Another study analyzed the effectiveness of testing on asymptomatic cases with the SEIR model (*2*). In the scenario where testing was performed on 5% of asymptomatic cases, compared to the scenario without testing, the peak size and number of deaths were reduced by less than half, and the end date of the epidemic was also reduced by more than 80 days (*2*). In addition, the earlier the test time, the more effective it was in mitigating the spread of COVID-19, and the more tests on asymptomatic infected people, the less the number of deaths (*2*). A study analyzing contact tracing policies in 138 countries demonstrated that comprehensive contact tracing is an important policy to reduce COVID-19 deaths, and that rapid detection of index cases and contact isolation are key to epidemic control (*3*). However, countries around the world implemented different tracing and testing strategies.

Contact tracing and testing strategies for each country differed according to their response strategies. China has implemented large-scale contact tracing and testing along with long-term city lockdown to eliminate the outbreak (*4-6*). China has successfully contained COVID-19 through these measures (*5*). Japan concentrated its contact tracing and testing capabilities on cluster identification (*7,8*). Japan was able to prevent the emergence of super-spreading events and large-scale outbreaks through their cluster approach (*7*). Although South Korea was not a country with a containment strategy, it achieved near-containment success in early stage of the epidemic through extensive tracing and large-scale testing (*2*). Drive-through and walk-through screening centers, temporary screening clinics, preemptive testing and contact tracing using digital information such as CCTV, mobile data signals and credit card usage history are understood as characteristics of South Korea's tracing and testing strategies (*9-11*).

It is not clear which contact tracing and testing strategies are effective to control the ongoing COVID-19. However, China's long-term containment strategy is difficult to sustain because it requires huge socio-economic costs (*4,12*). The mitigation strategy adopted by some countries have limitations in that the scale of damage caused by infectious diseases may grow to an uncontrollable level (*12*). Therefore, the suppression strategy can be an appropriate alternative to the containment strategy and the mitigation strategy, and South Korea is a country that has succeeded in controlling COVID-19 with the suppression strategy.

1.2. Literature review

South Korea expanded its testing capabilities in various forms, and had a response system that concentrated its testing capabilities on COVID-19 outbreaks. In South Korea, screening clinics were moved out of hospitals to expand testing capacity and reduce the risk of intra-hospital infections (*13*). In addition, drive-through and walk-through screening centers received a lot of attention (*9,10*). The drive-through screening centers had the advantage of being able to quickly test while minimizing contact with other people (*9*). In walk-through screening centers, there was a risk of inter-individual infection during the testing process, but this can be overcome with mobile technology in South Korea (*10*). South Korea was able to dramatically increase the number of tests by introducing these types of screening centers (*10*). Furthermore, preemptive testing was the main testing strategy to response COVID-19 outbreaks (*11*). South Korea effectively suppressed the first and second waves through these testing strategies and, as a result, succeeded in lowering R_t to below 1 (*14*).

According to a study analyzing the period when South Korea expanded its testing capacity to respond to COVID-19, when the number of tests increased by 1,000, the number of confirmed cases decreased by 14.5, and R_t decreased by up to 0.65 after two weeks (*15*). A study of scenario analysis using a mathematical modelling showed that the cumulative number of confirmed cases increased by more than 1.3 times as the detection rate increased (*16*). Another study using a mathematical model confirmed the result that the test should be maintained at the maximum level from the early stage to after the peak for an optimal response to COVID-19 (*17*). Lee et al. (2021) reported that the number of confirmed cases decreases by up to 60% if the time from contact with a confirmed case to isolation is reduced from 3 days to 2 days by 1 day through strengthening of tracking and testing capacity (*18*). In a research on the predominant of delta variant, contact tracing and strengthening contact quarantine were suggested as essential measures for controlling the spread of COVID-19 (*19*). It was analyzed that the high-intensity and rapid testing was effective in controlling the size of the epidemic even during the outbreak of Omicron variant (*20*). A review paper on NPIs in South Korea and Turkey concluded that South Korea and Turkey were able to control the spread of COVID-19 through effective social distancing, expanded testing capabilities, and smart contact tracing (*21*).

1.3. Purpose of this study

The purpose of this study is to analyze South Korea's response to conceptualize tracing and testing, and to investigate how tracing and testing affect COVID-19 transmission. In the next chapter, we conceptualized tracing and testing based on South Korea’s response to COVID-19 outbreaks, and explores the role of contact tracing and testing based on the proposed concepts. It also explores the criteria for tracking and testing for an effective COVID-19 control. In the third chapter, the association of tracing and testing with the spread of COVID-19 was investigated.

Chapter 2.
South Korea's response strategy to COVID-19

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2.1. Background

Containment, suppression, and mitigation strategy were proposed as Coronavirus disease 2019 (COVID-19) pandemic response strategy (*5*). Containment strategy aims to eliminate the transmission in community (zero incidence for several days) through stringent interventions such as lockdown, border closure, and extensive tracing and large-scale testing (*5*). Because containment strategy is difficult to sustain for a long time, many countries are responding to COVID-19 with suppression or mitigation strategy. Mitigation strategy aims to minimize the damage of high-risk population. Therefore, it allows time-varying reproduction number (R_t) above one ($R_t>1$). On the other hand, the suppression strategy takes measures to suppress R_t below 1 with the goal of minimizing transmission ($R_t<1$)(*5,22*). R_t is the average number of secondary cases of an infector during his or her infectious period and can be controlled by countermeasures and changing the behavior (*23*). Lockdown, social distancing, mandatory wearing of masks, restrictions on flights from high-risk countries, and temporary border closure were implemented as measures of suppression strategy in United States, Argentina, and Uganda (5). In addition, tracing and testing were proposed as essential case-based interventions of suppression strategy, but different approaches were suggested depending on the national capability (5). South Korea's response strategy is a suppression strategy, which did not take lockdown and border closure.

South Korea's successful COVID−19 epidemic control in early stage was remarkable compared to other countries that adopted suppression strategy. South Korea minimized the number of confirmed cases by maximizing the effect of suppression strategy based on extensive contact tracing and large−scale testing as known as 3Ts (Tracing−Testing−Treatment) strategy (*24,25*). The 3Ts strategy was a success factor that led South Korea to become a country that succeeded in controlling the spread of COVID−19 along with China, which implemented a containment strategy (*24−28*). Contact tracing and testing are the primary measures recommended by World Health Organization (WHO) and US Centers for Disease Control and Prevention (CDC) (*29,30*). WHO recommended contact tracing and testing in all scenarios (No cases, Sporadic cases, Cluster of cases, and Community transmission) to control COVID−19 transmission (*29*). Related capabilities are recommended to be expanded when these are insufficient (*29*). CDC suggested testing and contact tracing as preparedness and response capabilities to public health emergency (*30*). According to CDC’ s definition, testing is a capability to identify, characterize, and confirm the public health crisis, and various resource elements are presented to prepare and conduct testing (*30*). Contact tracing was presented as a resource element for conducting epidemiological investigation (*30*).

Contact tracing is a measure to identify and quarantine contacts suspected of having been infected (even currently not ill) in close contact with infected (*31–34*). Detection and timely quarantine of asymptomatic or pre-symptomatic cases can lead to reduce uncontrolled transmission, which can effectively contribute to the prevention of further spread (*35*). Contact tracing also enables effective focus of response capabilities on the population-at-risk (*35*). Testing is a measure that contributes to the prevention of transmission through rapid detection and isolation of cases (*34*). Increase in testing is known to be effective in reducing size of epidemic (*15,36,37*). WHO has recommended keeping test positive rate below 5% to maintain a sufficient number of tests or keep number of infected stable in the community (*38*). Rapid testing with social distancing was recommended as an essential measure to prevent large outbreaks (*39*).

Since the effect of contact tracing is affected by basic reproduction number (R_0) and fraction of asymptomatic infection, contact tracing alone cannot contain COVID-19 pandemic, which has a high transmission rate and a large fraction of silent transmission. (*40*). However, effective tracing and testing strategies are not proposed (*5,22,35*). Therefore, general criteria to maximize the effect of tracing and testing is needed. In particular, South Korea can be a reference model for suppression strategy.

This study conceptualized contact tracing and testing performed in South Korea through literature review on South Korea's response. In addition, we developed a conceptual model to explore effective tracing and testing strategies. Therefore, the objectives of this study are to suggest a general criterion for tracing and testing based on South Korea's experience, and to propose a framework to assess tracing and testing.

2.2. Methods

In this chapter, we reviewed several papers on South Korea' s response to COVID-19 outbreaks. In addition, a few papers on COVID-19 response of United States and China were included to compare the response of other countries. Finally we reviewed 9 papers, including 6 on South Korea, 2 on United States and 1 on China. These papers described timeline of outbreak, number of cases and tests, and the response of the health authorities. These features were reconstructed to capture the concept of tracing and testing.

A conceptual model to explore the process of tracing and testing was developed based on the concept of tracing and testing. SEIR model was used in this section, and quarantine compartment (Q) was included to the model for further understanding the process of tracing and testing.

2.3. Results

2.3.1. South Korea's response to COVID-19

South Korea has expanded its testing capabilities to overcome the limitations of contact tracing to response against COVID-19. In the early stage, South Korea strengthened quarantine for those arriving from abroad and conducted tests on suspected cases who visited in areas where COVID-19 is spreading or who had symptoms related to COVID-19. In addition, through contact tracing and testing, efforts were made to find exposed persons and source of infection. On February 7, 2020, 3 cases were confirmed, and additional investigation revealed an outbreak related to Zumba classes (*41*). Epidemiological investigators traced 1,687 contacts, and among them, 116 cases were confirmed. In addition, 8 Zumba instructors were identified as the source of infection (*41*). However, as the number of confirmed cases increased, South Korea's contact tracing capabilities reached its limit.

South Korea actively responded by tracing groups with increased risk of infection and testing all individuals in traced groups to overcome the limitations of contact tracing. The first wave in South Korea started with Shincheonji Church (hereafter S.Church) in Daegu (*42*). Although the index case of S.Church had symptoms related to COVID-19, she was tested late, and her source of infection was not identified (*42*). As a result of contact tracing on the index case, about 1,000 persons who attended the same worship service were classified as contacts and tested. However, as the number of confirmed cases in S.Church increased, the health authority changed response strategy to testing all members and related persons (*n=10,220*) in consideration of the possibility of a large-scale outbreak in S.Church (*42*). As a result of testing on S.Church, 4,137 confirmed cases were identified (*42*).

Tracing on groups and large-scale testing strategy for all members was continued in South Korea. After a worker of a call center in Seoul, South Korea, was confirmed in March 2020, epidemiological investigators determined that the possibility of outbreak within the call center was high, considering the characteristics of call center (*43*). All workers of the call center, residents and visitors of the building were tested (*n=1,143*) and

96 confirmed cases were identified (*43*). Related to this outbreak, a nurse at a long-term care hospital in Bucheon, South Korea, was confirmed (*44*). 22 hospital workers who had the same working hours and all residents were classified as contacts, but all workers and residents were tested (*n=227*), and there were no additional cases (*44*). In March 2020, 3 confirmed cases were reported among visitors of a spa facility in Cheonan, South Korea (*45*). The health authority conducted tests on all workers and visitors (*n=2,245*) in the spa facility and the building. As a result, 7 additional confirmed cases were found (*45*). A large-scale testing strategy was also implemented in the Itaewon club outbreak in May 2020 (*46*). After social distancing was relaxed in South Korea on May 6, 2020, confirmed cases continued to occur at several clubs in Itaewon, Seoul, South Korea (*46*). In response, the Seoul Metropolitan Government and the health authorities conducted a nationwide large-scale testing by tracing all visitors to the club and people around the club. 41,612 people related to the Itaewon club outbreak were tested, and 96 confirmed cases were identified (*46*).

Temporary screening center was a new strategy in South Korea for prevention sporadic infections in the community. Temporary screening centers were operated in the Seoul metropolitan area at the beginning of the 3rd wave, and as the number of confirmed cases spread nationwide, temporary screening centers were also expanded to the whole country. Unlike previous waves that started from outbreaks within groups, the third wave in South Korea was driven by a small outbreak in community with unknown source of infection (*47*) and was due to spread by pre-symptomatic cases and asymptomatic cases.

Therefore, suppression through tracing became difficult, and temporary screening centers were introduced as a strategy to find pre-symptomatic cases and asymptomatic cases in the community. The testing strategy in each reviewed paper were summarized in Table 2-1.

Table 2-1. Testing strategy by risk of infection in each reviewed paper

Author (year)	Place	Risk group	Background risk	Risk of infection: Increased risk	Risk of infection: High risk	No. tested	No. cases
Park et al. (2020)	Seoul, Korea	Call center	Non-visitors	All visitors, workers and residents in the building	Workers in the call center	1,143	97
Kim et al. (2021)	Daegu, Korea	S.Religious group	Non-members	All members	Members who attended in the same worship service as the index case	10,220	4,137
Bae et al. (2020)	Cheonan, Korea	Fitness center	Non-visitors	All visitors, workers in the buildings	Students in Zumba classes and contacts in other places	1,687	116
Han (2020)	Jinju, Korea	Spa facility	Non-visitors	All visitors, workers in the buildings	People who were in the sauna at the same time as the confirmed cases	2,245	10

Table 2-1. Testing strategy by risk of infection in each reviewed paper (continued)

Author (year)	Place	Risk group	Background risk	Risk of infection		No. tested	No. cases
				Increased risk	High risk		
Kim (2020)	Bucheon, Korea	LTCH[a]	Non-visitors	**All patients and healthcare workers**	Patients and healthcare workers who had come into close contact with confirmed cases	227	0
Kang et al. (2020)	Seoul, Korea	Iteawon nightclubs	All residents and visitors	**All visitors of nightclubs and people who have stayed in the vicinity of nightclubs for more than 30 minutes**	Unknown	41,612	246
Cao et al. (2020)	Wuhan, China	Wuhan	**All residents in Wuhan**	Unknown	Unknown	9,899,828	300
Telford et al. (2020)	Georgia, USA	LTCFs[b]	Non-member of LTCFs	**All residents and staffs**	Residents and staffs with symptoms	2,022	15

[a]Long-term care hospital, [b]Long-term care facilities

2.3.1.1. Contact tracing and tracing−related testing

South Korea's tracing and testing strategy can be divided into 3 types: contact tracing and tracing−related testing, group tracing and preemptive testing, and testing on untraced individuals (See Figure 2−1). First, contact tracing and tracing−related testing is the most primary action to identify persons suspected of having been in close contact with an infected, to assess their exposure, and to quarantine them. Contact tracing is divided into forward tracing and backward tracing according to the tracing direction. Backward tracing is an action to find the source of infection, and it is a process of finding contacts during the latent period of a confirmed case (Figure 2−1A) (*33,48,49*). Forward tracing is an action to find contacts exposed to infectious disease by an infector, and it is a process of finding individuals who were in contact during the infectious period of the infector (Figure 2−1B) (*33,48,49*). In South Korea, bidirectional tracing, which performed both forward and backward tracing, was actively performed (Figure 2−1C) (*48*). In addition, contacts found through contact tracing were tested immediately to screen for infection, and negative contacts were quarantined for several days. South Korea was able to contain the spread of COVID−19 in the early stage of the pandemic through bidirectional contact tracing and quarantine contacts.

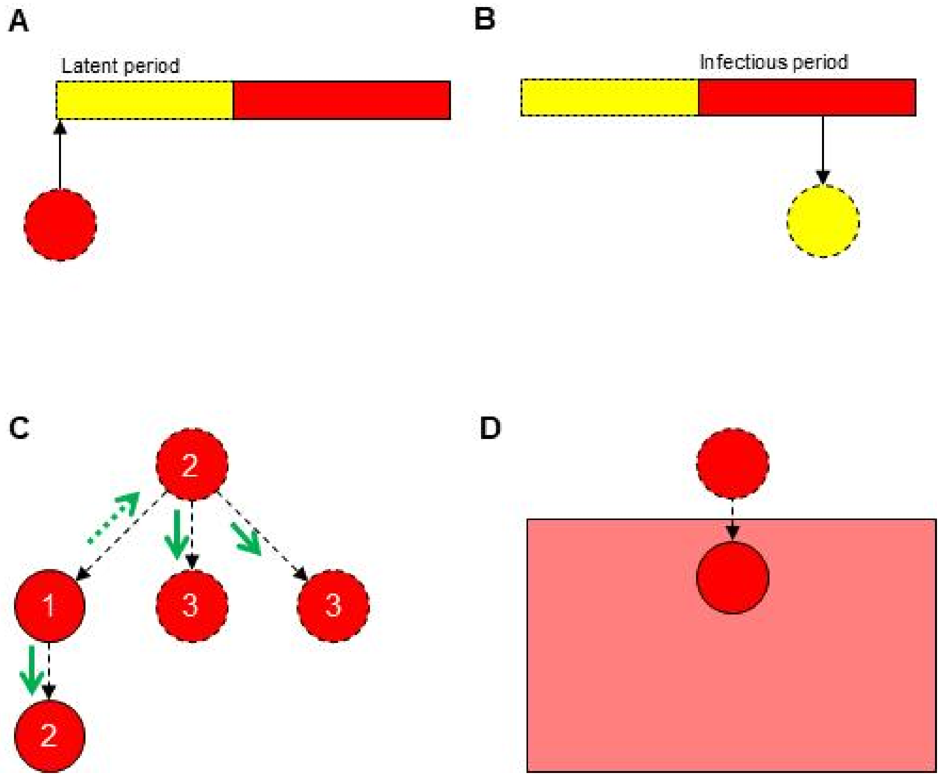

Figure 2-1. Types of tracing and source of infection

Note. Solid circles are cases who were detected and dashed circles are cases who were not detected yet. Red box indicates a potential cluster. Dashed red circle over the box is an unknown primary case and solid red circle in the box is the index case of the potential cluster.

2.3.1.2. Group tracing and preemptive testing

The group tracing and preemptive testing strategy was defined as tracing of a group suspected of outbreak and testing on those related to the traced group (Figure 2-1D) (*11*). A group suspected of outbreak is a group in which the risk of infection is increased when compared to the background risk. In South Korea, digital information such as GPS, mobile data signals, and credit card usage history was used for group tracing (*50*). Preemptive testing is the screening of all persons in the traced group and is performed regardless of symptom onset or exposure assessment. Quarantine of persons in the traced group is optional. Preemptive testing strategy was not only implemented in South Korea, but also conducted in other countries to find asymptomatic cases in groups (*51-53*). A study on long-term care facilities (LTCF) in the United States reported that preemptive testing was effective in blocking the spread of COVID-19 in LTCFs (*51*). In Wuhan, China, after the city lockdown, all citizens were tested ($n=9,899,828$), and 300 asymptomatic cases were identified (*53*). Group tracing and preemptive testing was a complementary strategy to contact tracing.

2.3.1.3. Testing on untraced individuals

Untraced individuals divided into two types. The first type is people who meet the criteria for suspected case presented in the guidelines, and the second type is people who do not meet the criteria for suspected case. At the beginning of the pandemic, testing was performed only on those who met the criteria for suspected case among untraced individuals. This can be defined as a suspected case testing, and it is a testing strategy that can efficiently operate the testing capabilities. Index cases of outbreaks mentioned above were mainly identified by suspected case testing. Because it was difficult for pre-symptomatic and asymptomatic cases to participate in the testing, South Korea implemented a new test policy that allowed people unmet to criteria for suspected case to participate in testing. This strategy of testing anyone who wishes to be tested regardless of the criteria for suspected case was defined as open testing. Open testing is a testing strategy for detecting pre-symptomatic and asymptomatic cases.

2.3.2. Conceptual model based on South Korea's experience

2.3.2.1. SEQIR model

We developed a new model based on the concepts of tracing, testing and quarantine in South Korea (Figure 2). The proposed model has 5 compartments: S, E, Q, I, and R. The S is a susceptible group without immunity to COVID-19 caused by vaccination or natural infection. People who have been in contact with an infected person but are not yet infectious move from S to E. E is an exposed group by COVID-19 cases, and individuals belonging to this compartment are subject to contact tracing and group tracing. Each concept of tracing was written in subscript in the Figure 2-2. Cases confirmed by testing belong to infected group and are divided into 4 types according to the results of tracing, testing and quarantine.

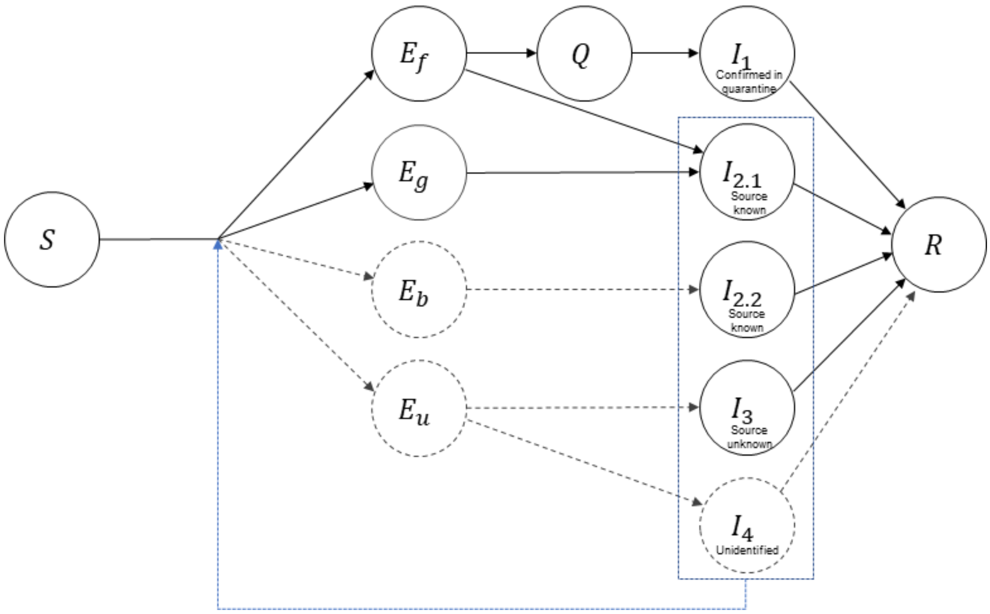

Figure 2-2. SEQIR model

Note. Solid lines and circles are observed in real world but dashed lines and circles are not detected. Blue square and arrow refer to primary infector and contact, respectively.

2.3.2.2. Case types by proposed model

I_1 was defined as cases confirmed in quarantine. Some contacts were identified before their infectious period by forward tracing and were quarantined to prevent further spread of COVID−19. Therefore, cases of I_1 have no further transmission due to timely quarantine.

I_2 was defined as a non−quarantined cases with a known source of infection. I_2 is divided into $I_{2.1}$ and $I_{2.2}$ depending on whether the source was known at the time of confirmation. $I_{2.1}$ was identified in forward tracing and group tracing but was confirmed positive for COVID−19 before quarantine. $I_{2.2}$ was not discovered by tracing, so the source was unknown at the time of confirmation, but the source was later identified. Since backward tracing performed in the reverse direction from the spread of infection, it is conducted after confirmation. Therefore, the number of $I_{2.2}$ among the new confirmed cases reported on a day is unknown, and $I_{2.2}$ can be distinguished from I_3 after a few days.

I_3 means an untrace confirmed case. They were not detected by tracing and the source was not traced after confirmation. People who participated in suspected case testing or open testing did not have epidemiological linkage. When they were confirmed, the source of infection was also unknown. Backward tracing for them was performed but was failed due to recall bias and large proportion of asymptomatic case (*33,42,49*). Cases who were not traced and tested belong to the unidentified group (I_4), which is not included in the number of confirmed cases because this group is not observed. The types of confirmed cases by tracing, testing and quarantine are shown in Table 2-2.

Table 2-2. COVID-19 case types

Category	Tracing	Testing	Quarantine	Case type[a]	Property of case type
1	Forward tracing	Tracing-related testing	Quarantine	I_1	Confirmed in quarantine
2	Forward tracing	Tracing-related testing	Non-quarantine	$I_{2.1}$	Source known
3	Backward tracing	Tracing-related testing	Non-quarantine	$I_{2.2}$	
4	Group tracing	Preemptive testing	Non-quarantine	$I_{2.2}$	
5	Untraced	Suspected case testing	Non-quarantine	I_3	Source unknown
6	Untraced	Open testing	Non-quarantine	I_3	

[a]See text for detailed definitions of case types

Case types were applied to the reviewed papers (Table 2−3). I_1 could be classified into 2 cases from the Spa facility outbreak and 108 cases from the fitness center outbreak. As for I_2, all confirmed cases of the S.Church, call center, and Itaewon club outbreaks (4,137 cases, 97 cases, and 246 cases, respectively) that performed group tracing and preemptive testing were classified as I_2. Since detailed classification is difficult due to the lack of information about the date of confirmation and quarantine, the index cases of these outbreaks were also classified in I_2. In addition, 5 cases of spa facility and 3 cases of fitness center cases can be classified as I_2. Finally, 3 index cases of spa facility outbreaks and 8 Zumba instructors identified as the source of infection for fitness center outbreaks were classified as I_3.

Table 2-3. Number of I_1, I_2, and I_3 in reviewed studies

Author (year)	I_1	I_2	I_3	cases
Kim et al. (2021)	0	4,137	0	4,137
Han (2020)	2	5	3	10
Bae et al. (2020)	108	3	8	119
Park et al. (2020)	0	97	0	97
Kan et al. (2020)	0	246	0	246

2.3.2.3. Novel indicators based on SEQIR model

Case types can be used as indicators for tracing and testing. Since each case type is determined by tracing and testing, the performance of tracing and testing can be assessed through fractions of each case type. First, the effects of comprehensive tracing and testing can be confirmed as traced proportion combined with I_1 and I_2. Keeping a high traced proportion is a goal of tracing and testing. In addition, fractions of each case type can be used to determine which tracing and testing capabilities are needed to be enhanced. In particular, I_1 is the goal of tracing and testing as the endpoint of tracing and testing (Figure 2-3). Therefore, when the fractions of I_2 and I_3 are high, it is necessary to try to reduce them and increase the proportion of I_1.

I_2 has cases of delayed forward tracing and group tracing and preemptive testing. If contact tracing is delayed, although the infectious period of a case may be shortened, additional forward tracing is necessary due to the high possibility of secondary infection. Since forward tracing on cases confirmed through group tracing and preemptive testing is also required, the continuous occurrence of I_2 may lead to a loop of forward tracing. In order to break this loop, it is necessary to have a faster forward tracing capability or to make group members quarantined when tracing groups.

I_3 refers to untraced cases. The proportion of I_3 may increase when there is an accumulation of infected persons in the community and the proportion of pre-symptomatic and asymptomatic cases is high. The increase in I_3 needs to be controlled because it may lead to additional transmission and large-scale outbreaks due to the increase of silent transmission. In order to prevent the continuous occurrence of I_3, strengthening the capability to conduct rapid contact tracing, and implementing group tracing and preemptive testing can be considered. In addition, through large-scale open testing, it is possible to lower the fraction of I_3 by trying to find pre-symptomatic and asymptomatic cases in the community.

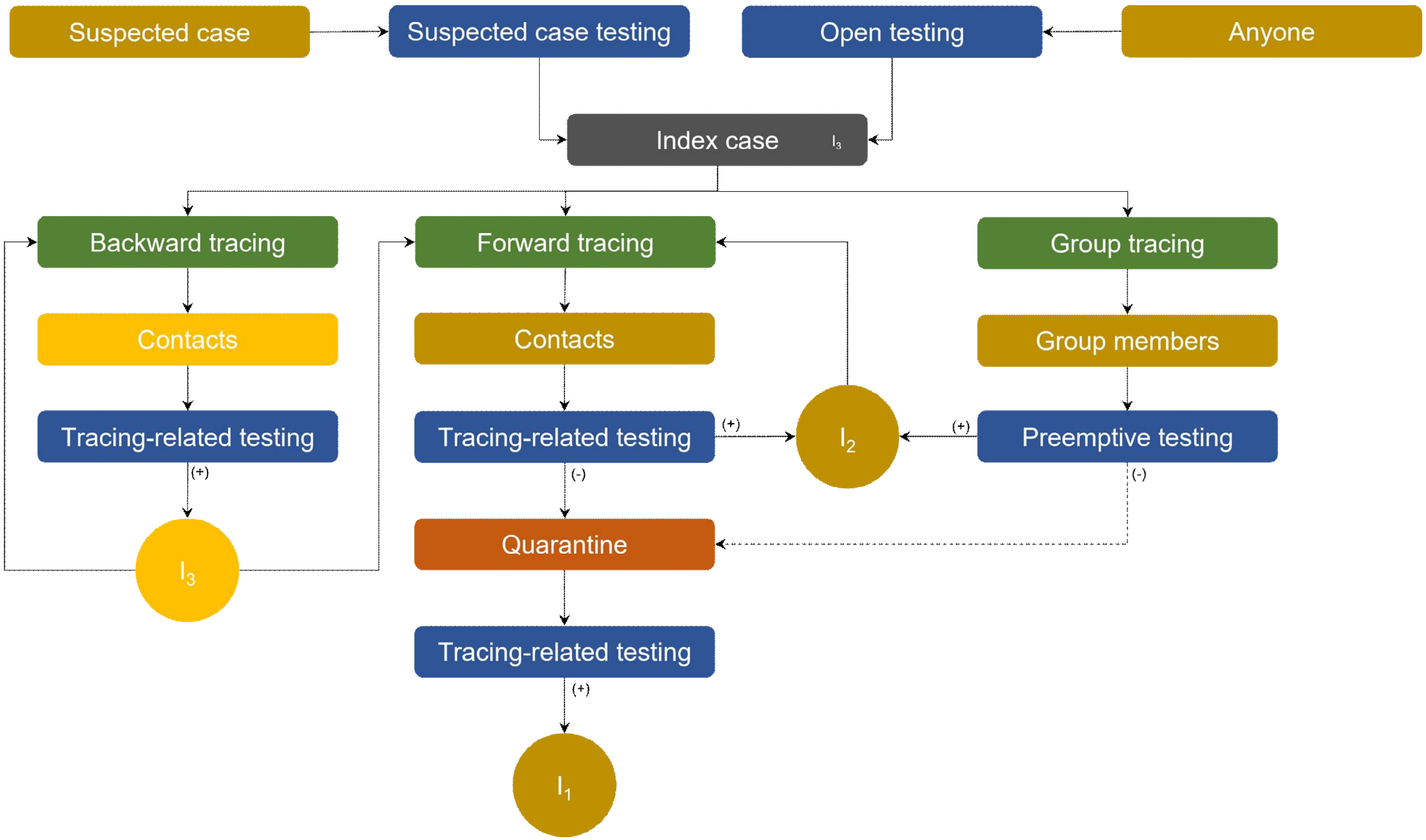

Figure 2-3. Algorithm of tracing and testing

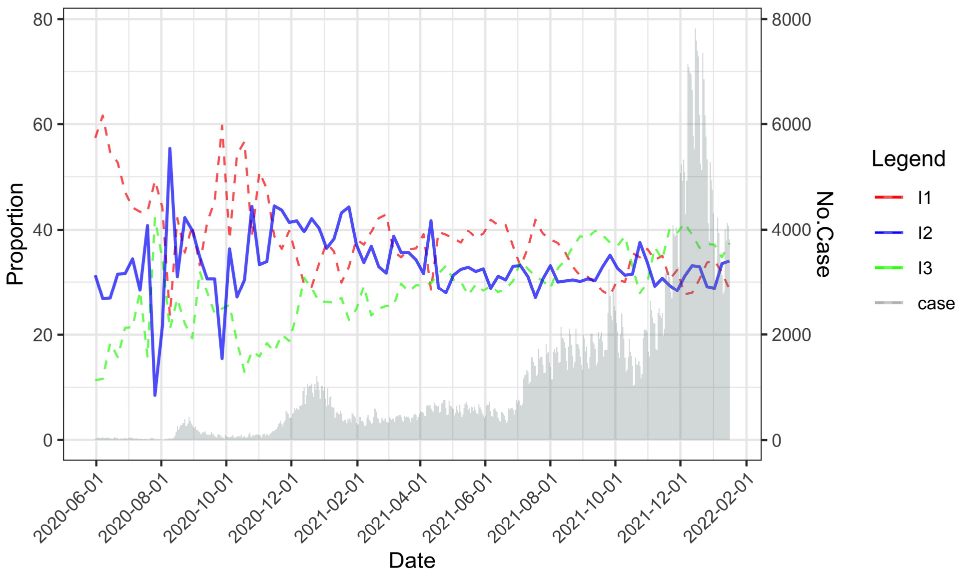

Figure 2-4. Time trends by case types in South Korea

Note. It was inferred that the decrease rate of I_3 (green dashed line) was moderated by increasing I_2 (blue solid line) when I_1 (red dashed line) was lowered during the spread of COVID-19 (3rd wave: November 2020 to January 2021, 4th wave: July to October 2021).

2.4. Discussion

In this study, we conceptualized tracing and testing performed in South Korea by analyzing papers on South Korea's response to COVID-19 outbreaks. In South Korea, not only forward tracing but also backward tracing was actively performed. Group tracing and preemptive testing, and open testing were performed to overcome the limitation of contact tracing in South Korea. In addition, we proposed SEQIR model to explore properties of case types according to tracing and testing strategies. In the model, the confirmed cases were classified into 4 types (I_1, I_2, I_3, and

I_4), and these case types can be used as the indicators to assess the performance of tracing and testing.

Contact tracing strategy in South Korea that simultaneously performed forward and backward tracing was an effective countermeasure to controlling COVID-19 because backward tracing can find cases not traced by forward tracing (Figure 2-1C). This finding is consistent with the results of previous studies that showed that bidirectional tracing allows finding a hidden transmission path (*33,48*). Moreover, these studies showed that bidirectional tracing shows better performance in controlling the spread of COVID-19 than performing forward tracing alone (*33,48*).

The case types found in this study were consistent with South Korea's risk assessment indicators. The proportion of I_1 is same as timely quarantine proportion (TQP), and it is an indicator that can comprehensively explain the effect of epidemiological investigation, testing, and quarantine (*54*). It is necessary to monitor the trends in I_1 to prevent the spread of COVID-19. Furthermore, maintaining a high proportion of I1 is a major challenge for countries to fight against COVID-19. However, during delta variant predominate, it was difficult to maintain a high proportion of I_1 because of its high transmission rate and capacity to escape from immune system.

The emerging of new variant can increase the proportion of untraced case (I_3). Untraced case is similar to unlinked case but is a more comprehensive concept. Since unlinked case means a confirmed case that has no linkage with the infector (*14,55*), a confirmed case discovered through group tracing and preemptive testing can be classified as an unlinked case, it is not included in untraced case. Rather, it is included in traced case who is controllable. Lowering the untraced proportion is another major challenge for countries, and it is expected to be achieved by increasing the proportion of I_2.

I_2 appears in all tracing process, so it is necessary to take an active and fast tracing to increase it. However, as mentioned above, if the scale of the epidemic is large due to the emergence of new variants, it is difficult to trace individuals suspected of having close contact with confirmed cases. In this case, group tracing and preemptive testing strategy can be alternative response strategy. This response strategy is expected to be able to identify super-spreaders and reduce cluster size, like Japan's cluster approach (*8*). As shown in the Figure 2-4, during delta variant predominate (after 2021 July) in South Korea, I_1 (red dashed line) decreased, but I_3 (green dashed line) did not rise, mostly remaining below 40%. According to the proposed model, it can be carefully inferred that this was achieved by group tracing and preemptive testing that made I_2 (blue solid line) constant.

Unlike previous studies, this study has the strength of conceptualizing detailed types of tracing and testing. In addition, although it was a study on South Korea's experience, it is expected that the proposed model can be generalized to other countries. On the other hand, this study did not address the social distancing and vaccination policies that play important roles in flattening the COVID-19 epidemic curve. In addition, statistical analysis using empirical data was not performed because this study aims to conceptualize South Korea' s tracing and testing strategies for responding to COVID-19. Lastly, this study may not include all papers that analyzed South Korea's response.

In conclusion, South Korea was able to overcome its lack of tracing capability by expanding its testing capabilities. In particular, group tracing and preemptive testing was a complementary strategy to contact tracing. Open testing was an effective testing strategy for the detection of pre-symptomatic and asymptomatic cases. Finally, case types found in this study could be used as indicators to evaluate tracing and testing and maintaining a high traced proportion was the key to suppression strategy.

Chapter 3. Relationship between tracing and transmission of COVID-19

Chapter 3.
Relationship between tracing and transmission of COVID-19

3.1. Background

Timely quarantine is the ultimate goal of contact tracing. Contact tracing is a measure to prevent the spread of infectious disease by reducing the uncontrolled transmission by identification of close contacts of a patient (*35*). Contact tracing, one of the recommended primary actions for infectious disease control (*29,30*), is defined as the process of finding individuals who have had close contact with an infected persons and assessing their risk of infection or exposure (*11*). Contact tracing can detect pre-symptomatic cases or asymptomatic cases, and subsequent quarantine of them can reduce the spread of infection in the community (*33,35*). In particular, large-scale contact tracing to find and quarantine all contacts before symptom onset is a prerequisite for containment strategy (*5*). However, not all contacts are quarantined in a timely manner.

Unlinked case can be regarded as a case who was not timely quarantined when he or she was confirmed. The unlinked case is defined as a case who is not connected to the primary case (an infector) in the transmission network (*55*). Several studies have presented the characteristics of unlinked cases. Chong et al. (2021) (*55*) evaluated that unlinked cases were related to the weekly number of confirmed cases and time to hospitalization. In addition, almost half (46.5%) of unlinked cases were index cases of secondary infection, and it was observed that additional transmission occurred mainly in homes, restaurants, and workplace (*55*). In particular, it has been reported that there is a higher probability of secondary transmission in the home than other settings (*55*). Ryu et al. (2021) compared the characteristics of the first and second waves during the COVID-19 epidemic in South Korea, and unlinked cases accounted for about 20% of local cases (*14*). Ryu et al. interpreted this proportion as a relatively low figure, as a result of maintaining extensive investigation until the second wave in South Korea (*14*).

Few studies have analyzed the association between unlinked cases and the spread of COVID-19. A study analyzing the characteristics of the COVID-19 epidemic in Korea reported a high positive correlation ($r>0.5$) between unlinked cases and the number of confirmed cases (*56*). Also, a significantly positive correlation ($r=0.39$) between unlinked cases and the number of confirmed cases was confirmed in a study conducted in Hong Kong (*55*). However, this correlation analysis did not take into account the characteristics of the time series data.

Untraced case is more suitable than unlinked case for analysis to understand the effect of tracing and testing. The observed association between unlinked cases and COVID-19 transmission may be biased because unlinked cases contain a controllable case type. According to a previous chapter, cases confirmed through group tracing and preemptive testing can be controlled even if the primary cases are unknown. Because their source of infection is recorded as the traced group, they are included in unlinked cases but not untraced cases. Untraced cases are cases whose the source of infection had not been confirmed because it has not been traced in any way.

Case types can be divided into traced case and untraced case. However, there were no studies on the association between case types and COVID-19 epidemic. Most of the related study analyzed the association between the scale of tracing and testing and the spread of COVID-19. As a result, the effect of case types on the transmission of COVID-19 is unknown. Therefore, this study examines the association between case types and transmission of COVID-19.

3.1.1. Hypothesis

In this study, we analyze the association between case types and the spread of COVID-19 using South Korea's surveillance data. The hypotheses to be tested in this study are as follows:

1) Timely quarantine and untraced cases would have a temporal relationship with COVID-19 transmission.

2) Increase in timely quarantined cases would reduce the risk of COVID-19 transmission.

3) Increase in proportion of untraced case would drive the spread of COVID-19 in community.

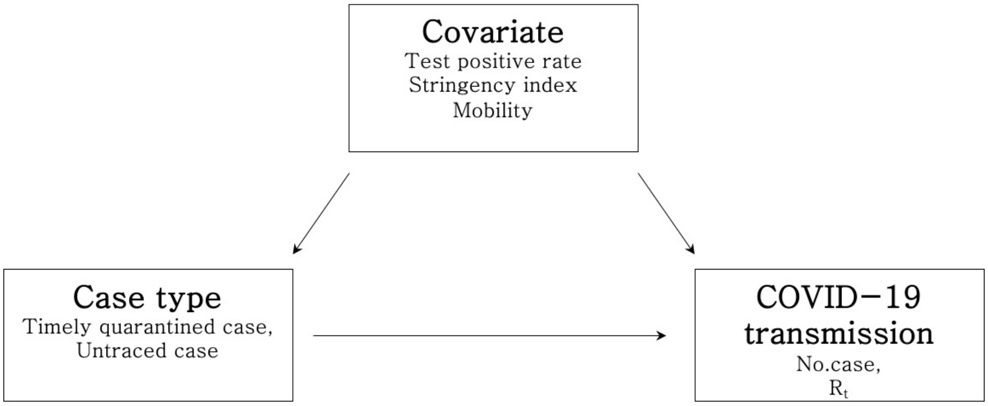

Figure 3-1. Conceptual framework of this study

3.1.2. Purpose of research

The purpose of this study is to analyze the relationship between case types and the transmission risk of COVID−19, and to explore the effects of tracing and testing in response to COVID−19.

3.2. Methods

3.2.1. Data and sources

COVID−19 surveillance data was collected from May 31, 2020 to December 31, 2021. The data used in this study are publicly available from the Korea Centers for Disease Control and Prevention (KDCA) and Our World in Data web site (www.ourworldindata.org).

Daily number of confirmed cases is newly reported number of confirmed cases with COVID−19. New confirmed cases are counted daily to the KDCA and disclosed through a press release. Therefore, we obtained daily number of confirmed cases from press released by KDCA. The confirmed case was divided into local case and import case, and in this study, the number of local cases was collected.

Time−varying reproduction number (R_t) is the average number of secondary cases infected by an confirmed case over his or her infectious period (*23*). R_t was estimated using daily number of confirmed case by "EpiEstim" package in R studio (*57,58*). The "EpiEstim" package estimates R_t retrospectively using the daily incidence and serial interval. In this study, different serial intervals were applied for different variants. KDCA disclosed the detection rate of the variant of concern (VOC), and the daily Rt was calculated by dividing the number of confirmed cases according to the detection rate. The serial intervals were 3.93days (*sd=4.85days*) for wild type (*59*), 3.6 days (*sd=4.89days*) for the delta variant (*60*), and 2.9 days (*sd=1.6days*) for the omicron variant (*61*). In South Korea, the delta variant was first identified on June 4, 2021, and became a predominant variant since July 25, 2021. Omicron variants were first reported on November 28, 2021, and became a predominant variant after January 21, 2022.

Timely quarantine proportion (TQP) is the proportion of confirmed cases who have been quarantined before symptom onset (*54*). This indicator shows the comprehensive effects of contact tracing, testing, and quarantine. In South Korea, if persons were classified as contacts, they were quarantined. Thus, TQP was measured as the proportion of confirmed cases who were contacts.

Untraced proportion (UTP) is the proportion of confirmed cases without the source of infection. In South Korea, the source of infection of all confirmed cases were traced. According to the tracing results, the source of infection of the confirmed case was divided into 6 categories: 1) import, 2) import-related, 3) medical or care facility, 4) community outbreak, 5) close contact with local case, and 6) unknown. The fraction of unknown source of infection was regarded as UTP. UTP in the same week were presented differently over time because of results of backward tracing. Therefore, to minimize bias due to this change, initial values were applied to the statistical analysis. TQP and UTP were used as risk assessment indicators representing tracing and testing capabilities in South Korea and disclosed by weekly through press released by KDCA.

Test positive rate (TPR) refers to the ratio of the number of positive cases to the total number of tests and is an indicator of the relative test performance compared to the epidemic size (*38*). An increase in the TPR means an increase in the number of infected people in the community or a decrease in the total number of tests (*38*). Therefore, TPR is a crucial indicator to be monitored. Daily TPR was obtained from press released by KDCA.

Stringency index (SI) is an index developed and published by The Oxford COVID-19 Government Response Tracker (OxCGRT) to compare countries' COVID-19 response policies worldwide (*62*). SI means the strictness of each country's COVID-19 response policy and is calculated based on 9 out of 22 indicators measured by OxCGRT (8 indicators for containment and closure and 1 indicator for health system). (*62*). In this study, daily SI was obtained from open dataset (*63*).

Mobility data was publicly available from Google' s COVID-19 Community Mobility Reports (*64*). Google opened mobility data to the public to monitor for response to COVID-19 (*64*). Google mobility (GM) has six categories (retail and recreation, grocery and pharmacy, residential, transit stations, parks, and workplace), presented as a percent change based on median mobility of each day of week before COVID-19 pandemic (from 3 January 2020 to 6 February 2020) (*64*). GM was measured based on the change in the number of visitors by place category of Google Map users, excluding the residential mobility (*64*). Residential mobility was measured based on the length of time spent in the residence (*64*). GM has been used in several studies on COVID-19 (*65-67*). Changes in mobility are known to be associated to the spread of COVID-19, and the effect does not appear immediately, but appears at intervals of 1 or 2 weeks (*66,67*). Considering the high correlation between GM categories and the fact that the category mainly used for COVID-19 risk assessment in South Korea was retail and recreation, it is assumed that this category represents South Korea's mobility.

Table 3-1. Data description and sources

Variable	Description	Source
Response variables		
Number of case	Number of local case	KCDA
R_t[a]	Average number of secondary cases caused by a single infected individual over his or her infectious period.	Estimated
Explanatory variables		
TQP[b]	Proportion of case quarantined before symptom onset	KCDA
UTP[c]	Proportion of case without source of infection	KCDA
Covariates		
TPR[d]	Positive case by total test	Our world in data
SI[e]	The stringency of the government′s response	OxCGRT
GM[f]	Percentage change of mobility	Google

[a]Time-varying reproduction number, [b]Timely quarantine proportion, [c]Untraced proportion, [d]Test positive rate, [e]Stringency index, [f]Google mobility

3.2.2. Statistical analysis

3.2.2.1. Descriptive analysis

Descriptive statistics (mean, min, and max) and ***correlations*** between response variables and explanatory variables were presented. Residual diagnosis was performed whether the observed correlation was estimated by autocorrelation of the residuals from each models. Residuals from correlation model were diagnosed through AutoCorrelation Function (ACF), Partial AutoCorrelation Function (PACF) and Ljung-box test.

3.2.2.2. Granger causality test

Granger causality test was performed for two purposes: 1) to investigate the causal relationship between the tracing and testing indicators (TQP and UTP) and the spread of COVID-19 (number of confirmed cases and R_t) in South Korea, and 2) to build regression models for further analysis of effect of tracing and testing on COVID-19 transmission. The Granger causality test is a statistical method that determines whether one time series Granger cause another time series (*68*). Granger causality test inferred Granger cause by comparing two predictive models using time series data (*68*). The Granger causality test models are as follows:

$$y_t = c_1 + \sum_{i=1}^{p} a_i y_{t-i} + \epsilon_{1t} \quad \text{(Equation 3.1)}$$

$$y_t = c_2 + \sum_{i=1}^{p} a_i y_{t-i} + \sum_{i=1}^{p} b_i x_{t-i} + \epsilon_{2t} \quad \text{(Equation 3.2)}$$

Equation 2.1 is a restricted model that predicts y at time t with the past value of y, and is an auto-regressive (AR) model of y with lag p. Equation 2.2 is an unrestricted model that predicts y at time t using past values of y and x. The null hypothesis (H_0) of the Granger causality test is that x does not Granger cause y (ie, $b_0 = b_1 = b_2 = \cdots = b_p = 0$, where b_p is coefficient of time series x in unrestricted model). Each test model was fitted as vector regressive model (VAR) and suitable lag (p) was selected based on the value of AIC. Granger causality test was performed by dividing the entire study period, before vaccination period, and after vaccination period to observe changes in the causal relationship according to the period. After fitting each VAR model, serial correlation was checked by Portmanteau test.

Before performing the Granger causality test, the stationarity test of the time series data was conducted. The stationarity of each time series data was tested by Kwiatkowski-Phillips-Schmidt-Shin Test (KPSS) test and Augmented Dickey-Fuller (ADF) test, When time series data were non-stationary, an appropriate difference was applied to the time series data. Since the null hypothesis of KPSS test is that the time series data are stationary, the test data is assumed to be stationary if the p-value of the test statistic is greater than the significance level (0.05). In the ADF test, the null hypothesis is that the time series is not stationary, so it is assumed that the time series is stationary when the p-value of the test statistic is below the significance level (0.05).

Granger causality tests for reverse direction were also performed. The "tseries" (for KPSS and ADF test) (*69*), "vars" (for model selection and granger causality test)(*70*), and "forecast" (for residuals diagnosis) (*71*) packages were used in this section.

3.2.2.3. Distributed lag model (DLM)

Distributed lag model (DLM) was used to explore the lagged effects of tracing and testing on the number of confirmed case. In this study, 6 models were developed based on the analysis period (whole period, before and after vaccination) and predictive variables (TQP and UTP). Through DLM, the effect and pattern of each lag week can be estimated, and the net effect of lag weeks can also be calculated (*72*). DLMs were built using the generalized linear model (GLM), and after fitting the model, the variance inflation factors (VIF) of the variables were checked. In modeling, it was assumed that the effect of tracing and testing occurred over 2 weeks.

The number of confirmed cases among the response variables was assumed to follow a quasi-Poisson distribution, taking over-dispersion into account. Seasonality did not appear in the two indicators of tracing and testing, but a long-term increase or decrease trend was found, so it was adjusted using the spline method. The "stats" (for glm), and "splines" (for spline method) (*73*) packages were used in R studio (*58*).

3.3. Results

3.3.1. Descriptive analysis

During the study period (2020. 5.31. ~ 2021.12.31.), the average number of confirmed case of COVID-19 was 1,040.1 (*sd=1410.5*) and R_t was 1.03 (*sd=0.17*) in South Korea. The tracing and testing indicators showed a symmetrical shape (Figure 3-2). Overall, TQP showed a decreasing trend and UTP showed an increasing trend. The mean of TQP was 38.4% (*sd=7.7*), and UTP was 28.3% (*sd=7.4*). The trends of each time series data were displayed in Figure 3-2 and the descriptive statistics were summarized in Table 3-2.

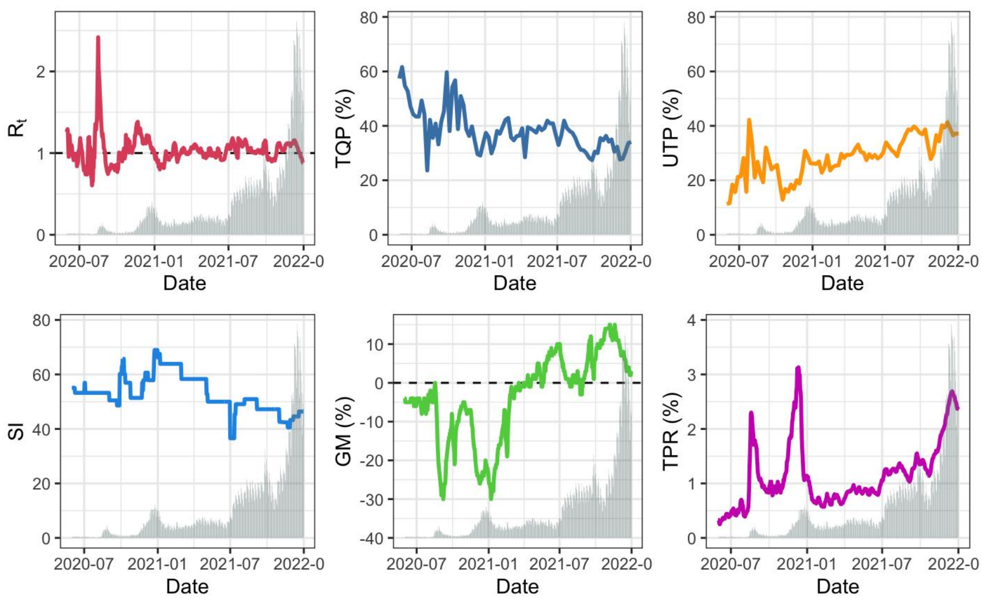

Figure 3-2. Trends of each time series

Table 3-2. Descriptive statistics of variables

Variable	Mean	Sd[a]	Min	Max
No. case	1040.1	1410.5	3.0	7825
Rt	1.03	0.17	0.6	2.42
TQP	38.4	7.7	23.6	61.6
UTP	28.3	7.4	11.3	42.2
TPR	1.15	0.60	0.25	3.13
SI	52.97	6.68	36.57	68.89
GM[b]	-3.66	11.18	-30.00	15.00

[a]Sd: Standard deviation, [b]Retail and recreation

Correlations between the number of confirmed case and tracing and testing indicators (TQP and UTP) were statistically significant. Timely quarantine proportion and the number of confirmed case had a negative correlation ($r=-0.51$) and untraced proportion and the number of confirmed case had positive correlation ($r=0.63$). However, correlations between Rt and each indicators were not observed. Furthermore, correlation between TQP and UTP was significantly strong ($r=-0.65$). The correlations were displayed in Figure 3-3. These associations are inferred to be observed due to the autocorrelation of the residuals from each model (Figure S3-1).

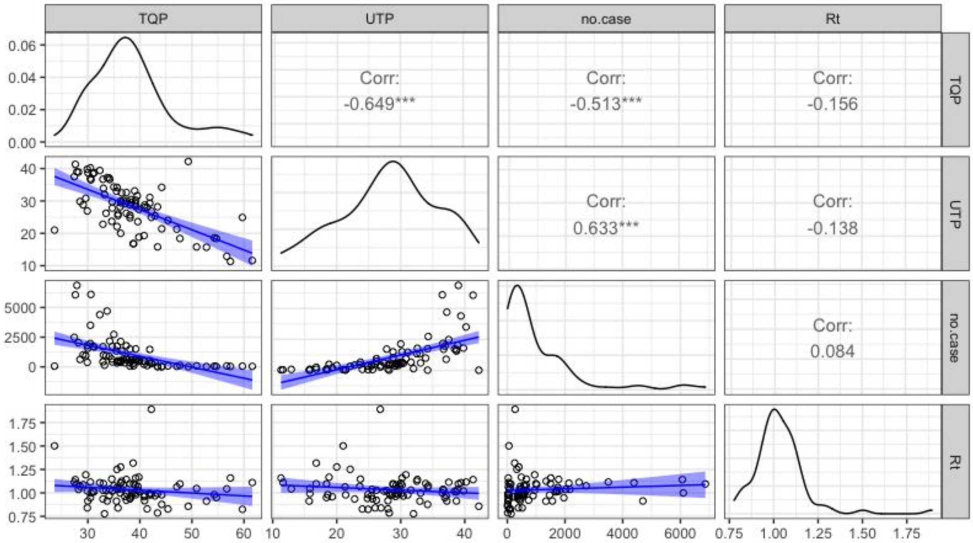

Figure 3-3. Correlation between response and explanatory variables

3.3.2. Granger causality

Stationarity was checked and non-stationarity were confirmed in the number of confirmed cases, TQP, and UTP *(Appendix B)*. These time series were first order differenced to make them stationary time series. All fitted VAR models did not show serial correlation.

The causal relationships between tracing and testing indicators and the spread of COVID-19 were summarized in Table 3-3. During the study period, timely quarantine by rapid contact tracing and testing appeared as a Granger cause of R_t. This causal relationship was confirmed before vaccination period as well, but after vaccination period, this relationship disappeared. However, during the period when the fully vaccinated population exceeded 20%, R_t rather appeared as a Granger cause of TQP.

It was confirmed that the Granger causality between UTP and R_t was bidirectional over the entire period. In the period before vaccination, untraced cases affected the R_t, and this relationship was changed in the period after vaccination. However, the relationship between UTP and R_t disappeared as fully vaccinated population increased.

After vaccination, UTP appeared as a causal factor of the number of confirmed cases. The same causal relationship was found even during the period when the immune population exceeded 20%.

Table 3-3. Causal relationship between tracing and COVID-19 transmission

		$\Delta No.Case$	R_t
(Whole period)	ΔTQP	Not G-Cause[a]	$\Delta TQP \rightarrow R_t$
	ΔUTP	Not G-Cause	$\Delta UTP \leftrightarrow R_t$
(Before vaccination)	ΔTQP	Not G-Cause	$\Delta TQP \rightarrow R_t$
	ΔUTP	Not G-Cause	$\Delta UTP \rightarrow R_t$
(After vaccination)	ΔTQP	Not G-Cause	Not G-Cause
	ΔUTP	$\Delta UTP \rightarrow \Delta No.Case$	$\Delta UTP \leftarrow R_t$
(Over 10% immunization)	ΔTQP	Not G-Cause	Not G-Cause
	ΔUTP	Not G-Cause	Not G-Cause
(Over 20% immunization)	ΔTQP	Not G-Cause	$\Delta TQP \leftarrow R_t$
	ΔUTP	$\Delta UTP \rightarrow \Delta No.Case$	Not G-Cause

[a]Granger-Cause

3.3.3. Effects of tracing and testing

TQP was found to be effective in significantly lowering the number of confirmed COVID−19 cases for two weeks. In the overall analysis period (Model 1), the RR of TQP for 2 weeks was 0.50 (*95% CI=0.38−0.65*). This was similarly confirmed in the pre−vaccination period (*Model 3; RR=0.42, 95% CI=0.29−0.59*) and post−vaccination period (*Model 5; RR=0.50, 95% CI= 0.35−0.72*). It was commonly observed in all models (Model 1, 3, 5) that the preventive effect of TQP on the number of confirmed cases disappeared after 2 weeks.

It was confirmed that UTP significantly increased the risk of the incidence COVID−19 cases for 2 weeks during the entire study period (*Model 2; RR=1.59, 95% CI=1.18−2.16*). In the post−vaccination period, it was confirmed that an increase in UTP significantly increased the number of confirmed COVID−19 cases (*Model 6: RR=2.27, 95% CI=1.50−3.45*). In contrast, the increment of UTP in the pre−vaccination period did not have significant effect on the number of confirmed cases (*Model 4; RR=1.07, 95% CI=0.59−1.93*). The 1−week lagged effect of UTP on the number of confirmed cases was commonly confirmed in Model 2(*RR=1.17, 95% CI= 1.06−1.29*) and Model 6 (*RR=1.31, 95% CI=1.14−1.51*).

The relative risk of TQP and UTP on the number of confirmed cases were displayed in Table 3−4 and Figure 3−4.

Table 3-4. Relative risk of tracing and testing on the number of COVID-19 cases

Model	Indicator	Period	Relative risk (95% CI[a])			
			Lag 0	Lag 1	Lag 2	Net effect
1	TQP	Whole period	0.59 (0.50-0.71)	0.79 (0.73-0.86)	1.06 (0.87-1.28)	0.50 (0.38-0.65)
2	UTP	Whole period	1.28 (1.02-1.61)	1.17 (1.06-1.29)	1.06 (0.85-1.33)	1.59 (1.18-2.16)
3	TQP	Before vaccination	0.78 (0.63-0.97)	0.75 (0.66-0.84)	0.71 (0.58-0.88)	0.42 (0.29-0.59)
4	UTP	Before vaccination	0.94 (0.64-1.37)	1.02 (0.84-1.25)	1.12 (0.77-1.61)	1.07 (0.59-1.93)
5	TQP	after vaccination	0.50 (0.38-0.65)	0.80 (0.71-0.90)	1.27 (0.95-1.71)	0.50 (0.35-0.72)
6	UTP	after vaccination	1.31 (0.96-1.80)	1.31 (1.14-1.51)	1.32 (0.95-1.84)	2.27 (1.50-3.45)

[a]Confidential interval

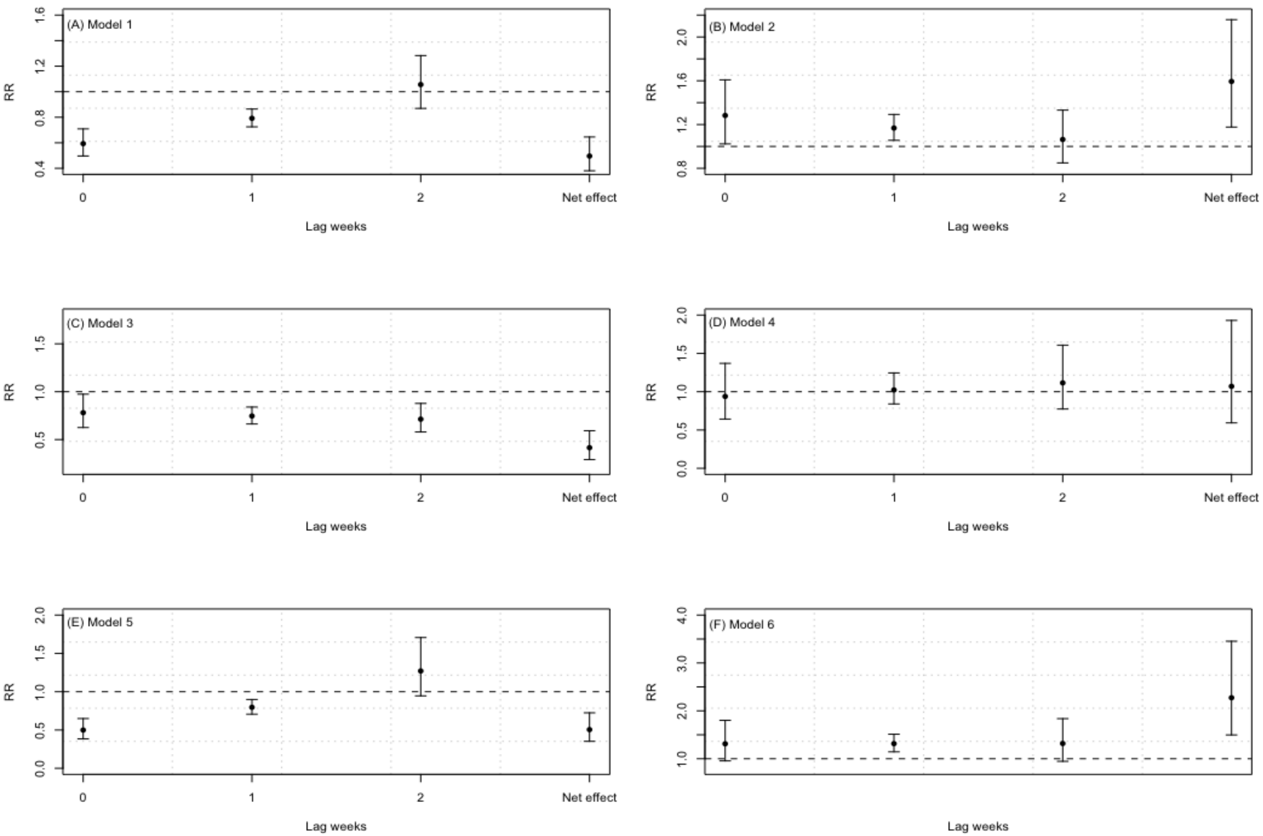

Figure 3-4. Distributed lag effects of contact tracing and testing on the number of confirmed case

3.4. Discussion

In this study, we found a causal relationship between tracing and testing indicators and the spread of COVID-19. The causal relationship of tracing and testing with R_t was clearly observed, but relationship with the number of confirmed cases was not observed. The causal relationship differed from time to time, and this could be the influence of mobility and variant. Timely quarantine through rapid contact tracing and testing had the effect of reducing the spread of COVID-19 within two weeks, and an increase in the untraced proportion was a risk factor accelerating the spread of COVID-19.

We identified changes in direction of Granger causality before and after vaccination. If the susceptible population were reduced due to vaccination and tracing and testing capabilities were maintained, it can be expected that the causal relationship that existed in the period before vaccination will continue in the period after vaccination. These change of Granger causality can be influenced by the size of the epidemic. In practice, after July 2021, South Korea implemented a vaccine pass policy, such as excluding those who have completed vaccinations from the gathering restrictions. In other words, as the immune population increased, their social activities would increase rapidly. As a result, the contact rate increased, possibly resulting in a lack of overall tracing and testing capabilities. This inference is consistent with a study that found the association between mobility and vaccination (*74*). In the study, mobility tends to increase along with the increase in the vaccination rate (*74*). In addition, impact of variants should be considered. Delta variant became predominant in South Korea after July 2021 and detection rate exceeded 90% in September 2021 when the fully vaccinated population exceeded 20%. Therefore, it is difficult to rule out the possibility that the tracing and testing capabilities were overwhelmed by the size of the epidemic grown due to increased mobility and delta variant.

Overall, the effects of timely quarantine disappeared after 2 weeks. Therefore, in order to control the spread of COVID-19 through tracing and testing, it is necessary to perform rapid and large-scale contact tracing and testing from the intial stage of epidemic and to continuously increase the number of confirmed cases under timely quarantine or reduce untraced cases. Since timely quarantine through contact tracing has obvious limitations, continuous suppression of the fraction of untraced cases through extensive group tracing and preemptive testing would be an alternative strategy.

It was analyzed that there was a risk that the number of confirmed cases more than doubled over 2 weeks due to untraced cases during the period after vaccination. This result implies the possibility that the number of confirmed cases increased exponentially because the overall UTP showed an increasing trend. This is similar with the real data in Figure 3-2. In particular, considering that there was no difference in tracing and testing policies on July 2021, the impact of untraced cases on the spread of COVID-19 at this time may be influenced by the emergence of delta variant and easing social distancing policy such as vaccine pass in South Korea.

This study has several limitations. First, this study did not include the entire period of South Korea's response to COVID-19. Therefore, it cannot be said that the associations observed in this study are also in the period not included. Second, the Granger causality test used in this study is not a causal reasoning method based on counterfactuals (*75*), and does not mean true causality. According to the ladder of causation presented by Pearl in his book (*76*), Granger causality is a causal reasoning method based on association and is included in the lowest rung, associational causality. On the other hand, counterfactuals is the highest rung, and it is a process of inferring causality between time series through activities such as imagining and retrospective causal inference. Associational causality infers causality based on the association of two time series under restricted assumptions. In the Granger causality test, a causal relationship is inferred based on assumptions such as the linearity of the two time series and the complete system (i.e. there is no unmeasured confounders) (*75, 77*). However, in the real world, the relationship between the two time series may be non-linear, and all factors related to the causality of the time series cannot be controlled completely. It was assumed that these assumptions were satisfied in this study as well. Therefore, the Granger causality observed in this study may have been confounded. Lastly, since it is not a study using individual-level data, we could not analyze the effect of tracing and testing on an individual's risk of infection with COVID-19.

In conclusion, this study demonstrated the importance of extensive and rapid tracing and testing. In particular, in order to effectively suppress the spread of COVID-19, it was necessary to maintain extensive tracing and testing strategy from the initial stage. Furthermore, in order to control the transmission of infection by untraced cases, it is necessary to perform group tracing and preemptive testing for a long time.

3.5. Supplementary data

Appendix A. Residuals diagnosis of correlation model

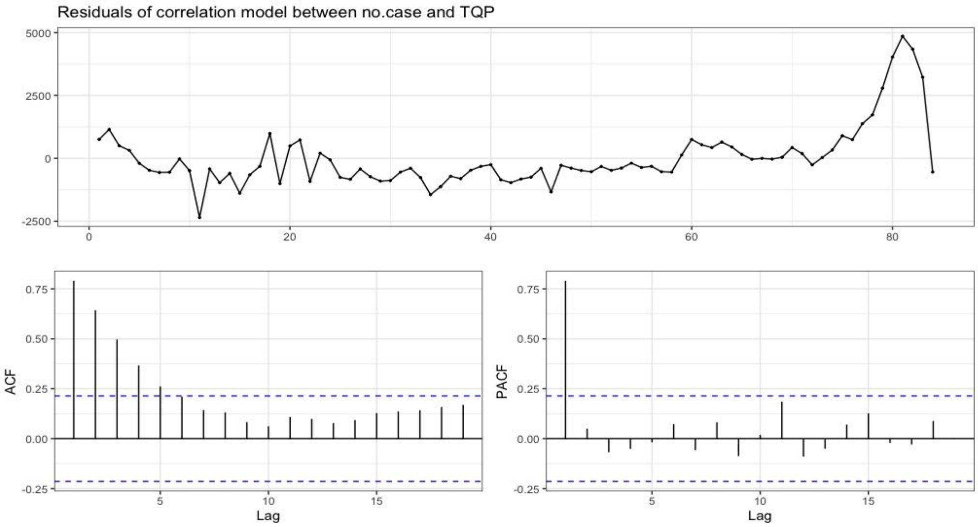

Figure S3-1. Residuals from correlation model of case and TQP

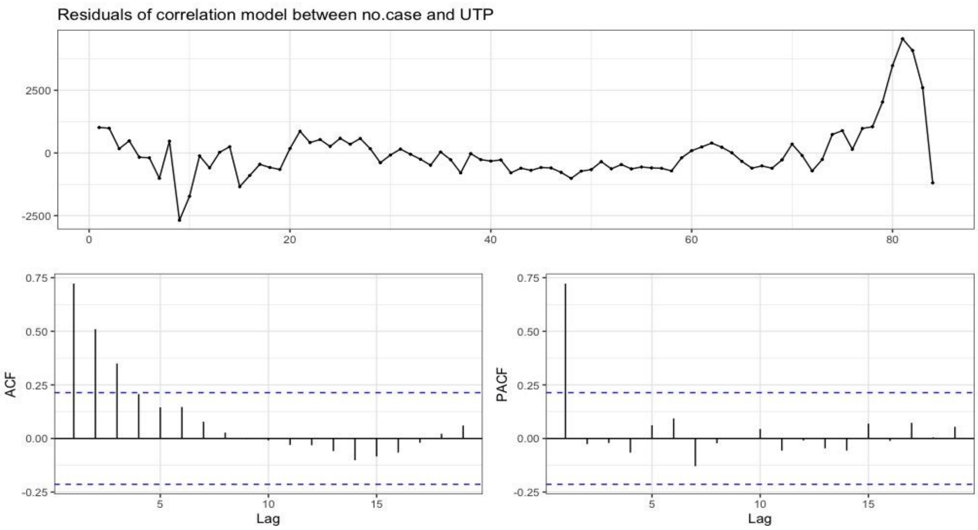

Figure S3-2. Residuals of correlation model of case and UTP

Appendix B. Stationarity of time series

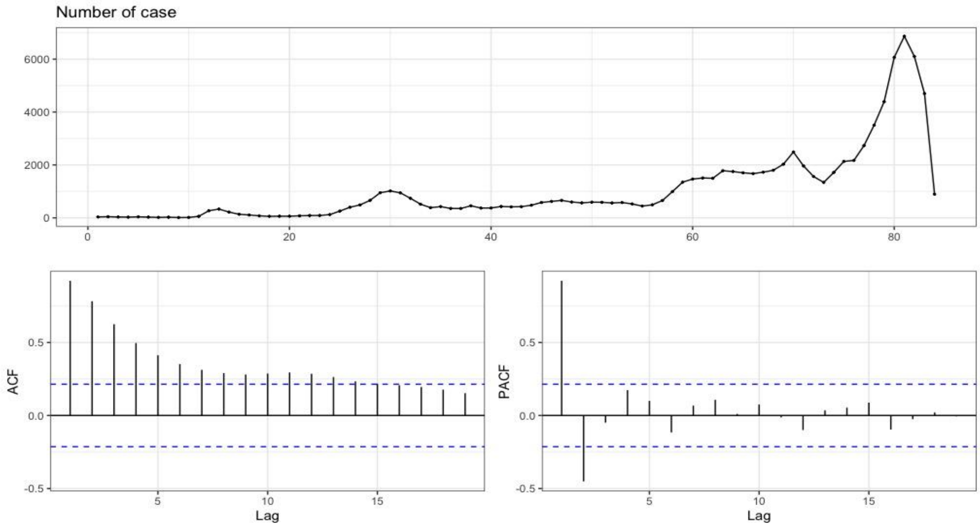

Figure S3-3. Time trend, ACF and PACF for number of case

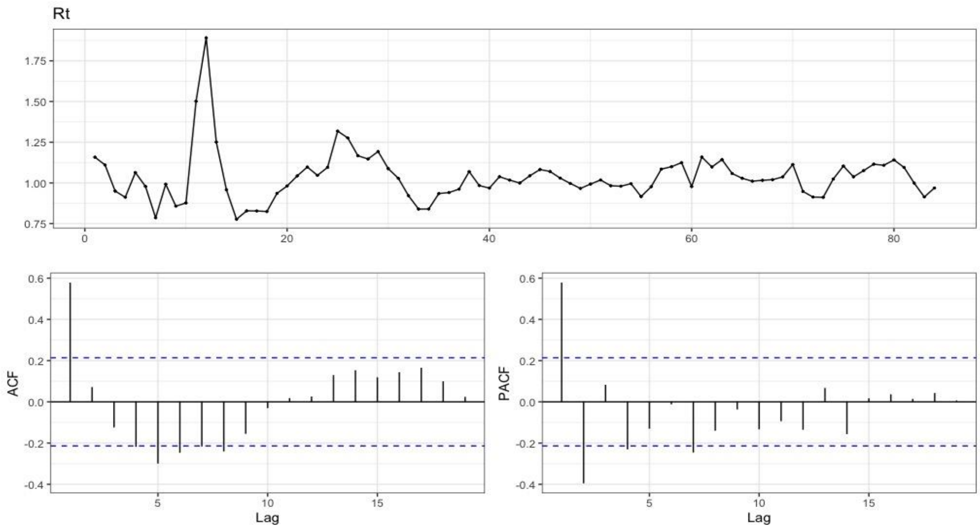

Figure S3-4. Time trend, ACF and PACF for Rt

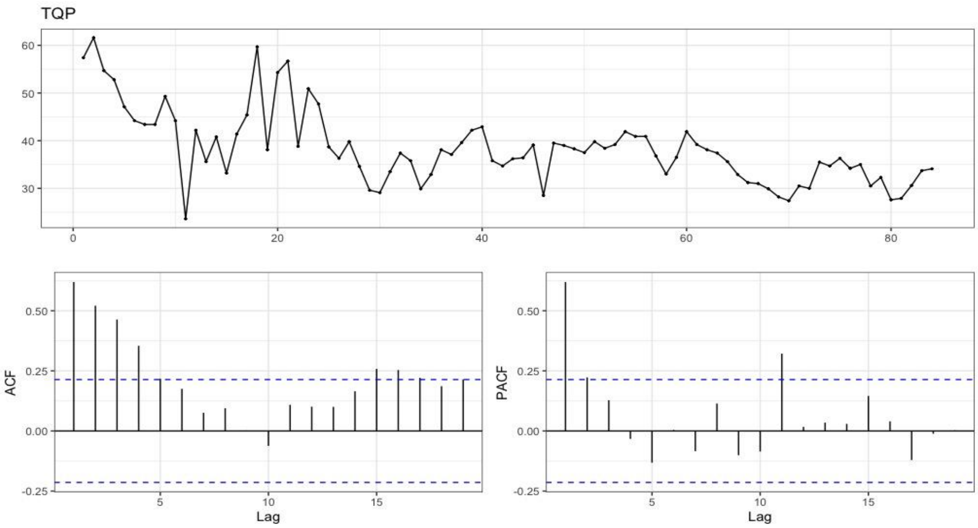

Figure S3-5. Time trend, ACF and PACF for TQP

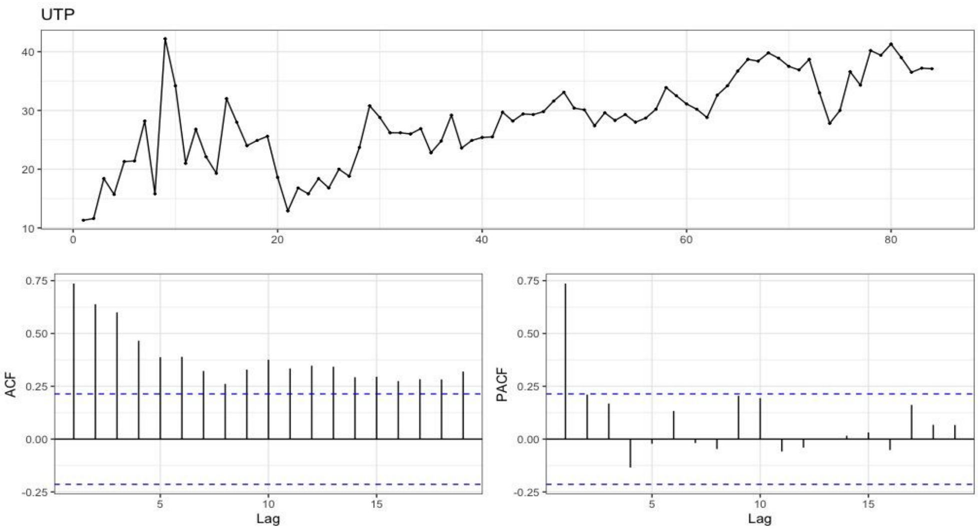

Figure S3-6. Time trend, ACF and PACF for UTP

Appendix D. Results of Granger causality test

Table S3-1. Granger causality test in hypothetical direction

Cause → Caused	Lag (p)	χ^2	df[a]	p-value
Whole period				
$\Delta TQP \rightarrow \Delta No.Case$	4	0.42	4	0.981
$\Delta UTP \rightarrow \Delta No.Case$	4	3.86	4	0.426
$\Delta TQP \rightarrow R_t$	2	7.87	2	0.020**
$\Delta UTP \rightarrow R_t$	3	14.85	3	0.002***
Before vaccination period[b]				
$\Delta TQP \rightarrow \Delta No.Case$	2	2.28	2	0.319
$\Delta UTP \rightarrow \Delta No.Case$	2	0.38	2	0.826
$\Delta TQP \rightarrow R_t$	2	5.03	2	0.081*
$\Delta UTP \rightarrow R_t$	4	10.80	4	0.029**
After vaccination period[c]				
$\Delta TQP \rightarrow \Delta No.Case$	4	0.31	4	0.989
$\Delta UTP \rightarrow \Delta No.Case$	4	8.73	4	0.068*
$\Delta TQP \rightarrow R_t$	1	0.34	1	0.562
$\Delta UTP \rightarrow R_t$	1	0.11	1	0.740
After 10% immunization[d]				
$\Delta TQP \rightarrow \Delta No.Case$	2	0.52	2	0.771
$\Delta UTP \rightarrow \Delta No.Case$	4	7.53	4	0.110
$\Delta TQP \rightarrow R_t$	2	0.38	2	0.829
$\Delta UTP \rightarrow R_t$	2	2.40	2	0.301
After 20% immunization[e]				
$\Delta TQP \rightarrow \Delta No.Case$	1	0.07	1	0.792
$\Delta UTP \rightarrow \Delta No.Case$	4	8.96	4	0.062*
$\Delta TQP \rightarrow R_t$	1	0.33	1	0.568
$\Delta UTP \rightarrow R_t$	2	4.21	2	0.122

[a]degree of freedom, [b]2020. 1.20. ~ 2021. 3.11., [c]2021. 3.12. ~ 2021.12.31., [d]2021. 7.16. ~ 2021.12.31., [e]2021. 9. 2. ~ 2021.12.31.

$^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

Table S3-2. Granger causality test in reverse direction

Cause → Caused	Lag (p)	χ^2	df[a]	p-value
Whole period				
$\Delta No.Case \rightarrow \Delta TQP$	4	2.53	4	0.639
$\Delta No.Case \rightarrow \Delta UTP$	4	0.95	4	0.918
$R_t \rightarrow \Delta TQP$	2	0.31	2	0.856
$R_t \rightarrow \Delta UTP$	3	8.42	3	0.038**
Before vaccination period[b]				
$\Delta No.Case \rightarrow \Delta TQP$	2	1.10	2	0.576
$\Delta No.Case \rightarrow \Delta UTP$	2	0.38	2	0.825
$R_t \rightarrow \Delta TQP$	2	0.08	2	0.962
$R_t \rightarrow \Delta UTP$	4	7.07	4	0.132
After vaccination period[c]				
$\Delta No.Case \rightarrow \Delta TQP$	4	2.96	4	0.565
$\Delta No.Case \rightarrow \Delta UTP$	4	1.76	4	0.780
$R_t \rightarrow \Delta TQP$	1	1.51	1	0.220
$R_t \rightarrow \Delta UTP$	1	4.15	1	0.042**
After 10% immunization[d]				
$\Delta No.Case \rightarrow \Delta TQP$	2	3.20	2	0.202
$\Delta No.Case \rightarrow \Delta UTP$	4	1.25	4	0.870
$R_t \rightarrow \Delta TQP$	2	2.34	2	0.310
$R_t \rightarrow \Delta UTP$	2	3.76	2	0.152
After 20% immunization[e]				
$\Delta No.Case \rightarrow \Delta TQP$	1	3.88	1	0.049**
$\Delta No.Case \rightarrow \Delta UTP$	4	0.64	4	0.958
$R_t \rightarrow \Delta TQP$	1	3.50	1	0.061*
$R_t \rightarrow \Delta UTP$	2	2.45	2	0.293

[a]degree of freedom, [b]2020. 1.20. ~ 2021. 3.11., [c]2021. 3.12. ~ 2021.12.31., [d]2021. 7.16. ~ 2021.12.31., [e]2021. 9. 2. ~ 2021.12.31.

$^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

Appendix E. Sensitivity analysis for Granger causality

Table S3-3. Granger causality test in hypothetical direction

Cause → Caused	Lag (p)	χ^2	df[a]	p-value
Whole period				
$\Delta TQP \rightarrow \Delta No.Case$	4	0.42	4	0.981
$\Delta UTP \rightarrow \Delta No.Case$	4	3.86	4	0.426
$\Delta TQP \rightarrow R_t$	2	7.87	2	0.020**
$\Delta UTP \rightarrow R_t$	3	14.85	3	0.002***
Before vaccination period[b]				
$\Delta TQP \rightarrow \Delta No.Case$	2	2.28	2	0.319
$\Delta UTP \rightarrow \Delta No.Case$	2	0.38	2	0.826
$\Delta TQP \rightarrow R_t$	2	5.03	2	0.081*
$\Delta UTP \rightarrow R_t$	4	10.80	4	0.029**
After vaccination period[c]				
$\Delta TQP \rightarrow \Delta No.Case$	4	0.30	4	0.990
$\Delta UTP \rightarrow \Delta No.Case$	4	8.49	4	0.075*
$\Delta TQP \rightarrow R_t$	1	0.36	1	0.547
$\Delta UTP \rightarrow R_t$	1	0.05	1	0.820
After 10% immunization[d]				
$\Delta TQP \rightarrow \Delta No.Case$	2	4.66	4	0.325
$\Delta UTP \rightarrow \Delta No.Case$	4	6.67	4	0.154
$\Delta TQP \rightarrow R_t$	2	0.23	2	0.892
$\Delta UTP \rightarrow R_t$	2	2.33	2	0.312
After 20% immunization[e]				
$\Delta TQP \rightarrow \Delta No.Case$	1	0.14	1	0.708
$\Delta UTP \rightarrow \Delta No.Case$	4	8.96	4	0.062*
$\Delta TQP \rightarrow R_t$	1	0.33	1	0.564
$\Delta UTP \rightarrow R_t$	1	0.01	1	0.924

[a]degree of freedom, [b]2020. 1.20. ~ 2021. 3.11., [c]2021. 3.12. ~ 2021.12.31., [d]2021. 7.16. ~ 2021.12.31., [e]2021. 9. 2. ~ 2021.12.31.

$^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

Table S3-4. Granger causality test in reverse direction

Cause → Caused	Lag (p)	χ^2	df[a]	p-value
Whole period				
$\Delta No.Case \rightarrow \Delta TQP$	4	2.53	4	0.639
$\Delta No.Case \rightarrow \Delta UTP$	4	0.95	4	0.918
$R_t \rightarrow \Delta TQP$	2	0.31	2	0.856
$R_t \rightarrow \Delta UTP$	3	8.42	3	0.038**
Before vaccination period[b]				
$\Delta No.Case \rightarrow \Delta TQP$	2	1.10	2	0.576
$\Delta No.Case \rightarrow \Delta UTP$	2	0.38	2	0.825
$R_t \rightarrow \Delta TQP$	2	0.08	2	0.962
$R_t \rightarrow \Delta UTP$	4	7.07	4	0.132
After vaccination period[c]				
$\Delta No.Case \rightarrow \Delta TQP$	4	2.72	4	0.606
$\Delta No.Case \rightarrow \Delta UTP$	4	1.70	4	0.791
$R_t \rightarrow \Delta TQP$	1	1.42	1	0.233
$R_t \rightarrow \Delta UTP$	1	3.86	1	0.050**
After 10% immunization[d]				
$\Delta No.Case \rightarrow \Delta TQP$	2	2.53	4	0.638
$\Delta No.Case \rightarrow \Delta UTP$	4	1.22	4	0.875
$R_t \rightarrow \Delta TQP$	2	0.90	2	0.637
$R_t \rightarrow \Delta UTP$	2	4.28	2	0.118
After 20% immunization[e]				
$\Delta No.Case \rightarrow \Delta TQP$	1	4.22	1	0.040**
$\Delta No.Case \rightarrow \Delta UTP$	4	0.64	4	0.958
$R_t \rightarrow \Delta TQP$	1	3.79	1	0.052*
$R_t \rightarrow \Delta UTP$	2	2.57	1	0.109

[a]degree of freedom, [b]2020. 1.20. ~ 2021. 3.11., [c]2021. 3.12. ~ 2021.12.31., [d]2021. 7.16. ~ 2021.12.31., [e]2021. 9. 2. ~ 2021.12.31.

$^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

Table S3-5. Temporal relationship between tracing and COVID-19 transmission

		$\Delta No.Case$	R_t
(Whole period)	ΔTQP	Not G-Cause[a]	$\Delta TQP \rightarrow R_t$
	ΔUTP	Not G-Cause	$\Delta UTP \leftrightarrow R_t$
(Before vaccination)	ΔTQP	Not G-Cause	$\Delta TQP \rightarrow R_t$
	ΔUTP	Not G-Cause	$\Delta UTP \rightarrow R_t$
(After vaccination)	ΔTQP	Not G-Cause	Not G-Cause
	ΔUTP	$\Delta UTP \rightarrow \Delta No.Case$	$\Delta UTP \leftarrow R_t$
(Over 10% immunization)	ΔTQP	Not G-Cause	Not G-Cause
	ΔUTP	Not G-Cause	Not G-Cause
(Over 20% immunization)	ΔTQP	$\Delta TQP \leftarrow \Delta No.Case$	$\Delta TQP \leftarrow R_t$
	ΔUTP	$\Delta UTP \rightarrow \Delta No.Case$	Not G-Cause

[a]Granger-Cause

Chapter 4.
Conclusion

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Conclusion

South Korea made efforts to prevent further spread of COVID-19 through rapid contact identification and quarantine. However, the capability of contact tracing reached its limit from the first wave that started in a religious group in February 2020. Group tracing and preemptive testing strategy was introduced as complementary strategy to contact tracing to suppress the spread of COVID-19 caused by large-scale outbreaks. This strategy had become a key tracing and testing strategy in South Korea, and is considered a factor that made rapid suppression of R_t during early stage.

Open testing introduced from the third wave in South Korea was also an effective testing strategy. From the third wave, the number of confirmed cases increased compared to previous waves, and open testing played a role in early detection of pre-symptomatic and asymptomatic cases in the community. Since July 2021, it was clearly observed that R_t maintained greater than 1, which is reasonable to interpret as the effect of changes in social distancing policy and the emergence of new variants.

Based on the above results, we suggest an effective tracing and testing strategy for successful suppression of the COVID-19 epidemic. First, rapid contact tracing must be performed for early contact quarantine. Timely quarantine has a clear effect on preventing further transmission of infection. Extensive tracing and testing such as group tracing and preemptive testing and open testing should be performed. These will keep a high traced proportion more than 60% and prevent silent transmission in the community. In addition, these tracing and testing strategies should be implemented from early stage of epidemic. Since the effect of timely quarantine disappears in a short time and the effect of preemptive testing appears after a few weeks, conducting such tracing and testing strategies from an early stage would be beneficial in controlling the spread of COVID-19. Finally, a rapid assessment of tracing and testing should be made. To this end, monitoring of the new indicators presented in this study will be absolutely necessary.

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국문초록

한국의 코로나19 대응에서 접촉자 추적 및 검사의 역할

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한국의 코로나19 확산 통제 성공은 억제 전략을 채택한 국가들 사이에서 괄목할 만한 성과였다. 한국의 광범위한 추적과 대규모 테스트가 그 성공 요인으로 주목받았다. 따라서 본 연구의 목적은 한국의 코로나19 대응 경험을 바탕으로 추적 및 검사를 통한 코로나19 통제를 위한 일반적인 기준을 제시하고, 추적 및 검사를 평가할 수 있는 새로운 틀을 제안하는 것이다. 또한 추적 및 테스트와 COVID-19의 확산 사이의 관계를 조사하는 것을 목표로 한다.

한국은 접촉자 추적 역량의 한계를 극복하기 위해 집단추적과 선제검사, 임시검사(open testing) 등을 도입하여 검사 역량을 확대했다. 이러한 한국의 추적 및 검사 전략에 바탕으로 개발된 SEQIR 모델에 따르면 COVID-19 확진자는 4가지 유형(격리 중 확진, 경로확인, 경로 미확인, 미식별)으로 나뉘며, 확진자 유형은 추적 및 검사를 평가하는 데 유용한 지표가 될 수 있었다.

이러한 코로나19 확진자 유형을 통한 추적 및 검사 지표를 이용하여 추적 및 검사와 COVID-19 유행과의 관계를 분석한 결과, 추적 및 검

사를 통한 접촉자의 조기 격리는 2주에 걸쳐 코로나19 발생 위험을 예방하는 효과가 있었다. 반면 경로가 확인되지 않은 미추적 확진자 비율이 높아지면 코로나19 발생 위험이 높아지는 것으로 확인되었다.

결론적으로 한국의 대규모 추적 및 검사 전략은 추적되지 않은 확진자의 발생을 억제하는 역할을 하였다. 한국은 집단 추적과 선제적 추적 전략을 통해 높은 추적 비율(60% 이상)을 유지함으로써 코로나19 유행을 억제할 수 있었다. 또한 신속한 접촉자 추적을 통한 접촉자의 조기 격리의 효과는 2주 뒤에 사라지기 때문에 추적 및 검사 역량을 최대한 유지하기 위한 노력이 필요하며, 이를 보완하기 위해 대규모 집단추적 및 선제검사 전략의 조기 시행이 요구된다.

주요어 : 코로나19, 추적, 검사, 집단추적, 선제검사, 격리, 감염경로
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