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Original Article

Effectiveness of containment strategies in preventing SARS-CoV-2 transmission

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ABSTRACT

Background: Despite substantial resources deployed to curb SARS-CoV-2 transmission, controlling the COVID-19 pandemic has been a major challenge. New variants of the virus are frequently emerging leading to new waves of infection and re-introduction of control measures. In this study, we assessed the effectiveness of containment strategies implemented in the early phase of the pandemic.

Methods: Real-world data for COVID-19 cases was retrieved for the period Jan 1 to May 1, 2020 from a number of different sources, including PubMed, MEDLINE, Facebook, Epidemic Forecasting and Google Mobility Reports. We analyzed data for 18 countries/regions that deployed containment strategies such as travel restrictions, lockdowns, stay-at-home requests, school/public events closure, social distancing, and exposure history information management (digital contact tracing, DCT). Primary outcome measure was the change in the number of new cases over 30 days before and after deployment of a control measure. We also compared the effectiveness of centralized versus decentralized DCT. Time series data for COVID-19 were analyzed using Mann-Kendall (M-K) trend tests to investigate the impact of these measures on changes in the number of new cases. The rate of change in the number of new cases was compared using M-K z-values and Sen's slope.

Results: In spite of the widespread implementation of conventional strategies such as lockdowns, travel restrictions, social distancing, school closures, and stay-at-home requests, analysis revealed that these measures could not prevent the spread of the virus. However, countries which adopted DCT with centralized data storage were more likely to contain the spread.

Conclusions: Centralized DCT was more effective in containing the spread of COVID-19. Early implementation of centralized DCT should be considered in future outbreaks. However, challenges such as public acceptance, data security and privacy concerns will need to be addressed.

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Introduction

Severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2), the cause of the coronavirus disease 2019 (COVID-19) pandemic, continues to cause major impact worldwide [1–3]. Nearly 500

million cases and over 6 million deaths have been recorded since the outbreak was first reported in early 2020 [4,5]. The virus continues to evolve, with emergence of new variants, triggering renewed waves of global infection [6–9]. Although mass vaccinations have been rolled out in most countries [10], the effectiveness of all the currently approved vaccines has been found to decrease over time [11–13]. Thus, the challenges of containing and controlling this pandemic remains at the forefront.

Control measures such as regional lockdowns and quarantine were deployed during the first wave of the pandemic in Wuhan, China [14,15]. Many countries followed suit and adopted travel restrictions and public closures during the early intense phase of the global outbreak [16–18]. These extreme lockdowns were not sustainable however owing to large economic and societal costs [1,19]. Moreover, these measures were not universally effective. For example, containment strategies, such as strict lockdowns which were implemented in countries like China and Singapore in the first wave of the pandemic, were fairly effective in controlling the transmission [14,20]. By contrast, countries such as UK and USA, which implemented mitigating strategies such as social distancing, school closures and national curfews, did not fare well in controlling the transmission [20,21]. Subsequently, digital contact tracing (DCT) was piloted in a few countries and subnational regions to track case exposure, vaccination status and test results [22]. This intervention was reported to be more effective in controlling the spread of the infection [22–24]. However, the relative efficacy of different control measures remains unknown. Public health officials need a comparative analysis of real-world data to make informed policy decisions that have major social and economic consequences. The implementation of these control measures at different times in several countries with reliable case reporting, created a natural experiment to study their effect on viral transmission.

We aimed to evaluate the relative effectiveness of public health preventive measures in containing viral transmission using real-world data. This has implications for effective control of the current and future pandemics of highly transmissible infectious diseases.

Methods

Data collection

Real-world data was collected for 18 different countries. The full details of the sources and corresponding references are provided in [Supplementary eTable 1](#). Data was used to compare the effectiveness of public health containment and mitigating measures, namely, social distancing, stay-at-home requests, lockdowns, and schools/events closure. Data were also collected for 15 countries/regions that implemented digital contact tracing (DCT). The full details of the sources and references for DCT is given in [Supplementary eTable 2](#).

The number of new confirmed cases of SARS-CoV-2, 30 days before and after the implementation of a control measure were obtained via an extensive international data search ([Supplementary eTable 1 and eTable 2](#)). Data for COVID-19 cases was retrieved for the period Jan 1 to May 1, 2020. Additional data on the enforcement of containment measures were obtained from PubMed, MEDLINE, Facebook, Epidemic Forecasting (<http://epidemicforecasting.org/>), and Google Mobility Reports.

Statistical analysis

Time series data for COVID-19 were analyzed using Mann-Kendall (M-K) trend tests to investigate the impact of containment measures on changes in the number of new cases, reproductive number (R), and population mobility. M-K and Kolmogorov-Smirnov (K-S) tests were used to determine if the number of new cases differed before and after a policy implementation. A positive (or

negative) z -value indicated that the number of new cases increased (or decreased) over time. A containment measure was classified as effective if there was a decreasing trend in the change of new cases ($z < 0$) or a reduction in the number of new cases (percentage change < 0) after its implementation. Sen's slope was calculated to estimate the magnitude of the trend. All statistical analyses were conducted using R statistical language (R Core Team (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>. Version 4.0.3).

Results

We analyzed COVID-19 data from 18 countries and regions (mainland China and Hong Kong were analyzed separately; [Supplementary eTable 3](#)). The real-world effectiveness for each of the 6 control strategies varied considerably ([Supplementary eTable 4](#)). This variation in effectiveness is shown in [Fig. 1](#) by the change in z -scores 30-days before and after deployment. COVID-19 control measures, in order of decreasing effectiveness, included centralized DCT (change in mean z -scores, -2.2), decentralized DCT (-0.78), social distancing ($+0.98$), stay-at-home requests ($+1.5$), lockdowns ($+1.6$), and schools/events closure ($+1.7$). Thus, it appeared that DCT was associated with a decrease in the transmission of new cases while conventional strategies were relatively ineffective in controlling the spread of the virus.

Conventional social measures

Daily number of new cases was higher even after the implementation of standard social containment strategies as shown by the standardized number of new cases 30 days before and after implementation ([Supplementary eTable 4](#)). Substantial viral spread could be observed even after lockdowns in all studied countries. A sharp escalation in the number of newly infected cases was observed in the United Kingdom (slope $+4514$ [SE 43.74]) and Germany ($+4723$ [109.1]). Relatively smaller increases were seen in South Korea ($+40.86$ [11.58]) and Israel ($+20.11$ [5.95]) after lockdown implementation. Stay-at-home orders also did not retard the increase in the number of new cases ([Fig. 1](#)). School and events closures were only partly effective in decreasing the magnitude of the rate of new cases in Japan (64.8 [16.41]) and ineffective in other countries, consist with a previous report [21]. Social-distancing measures also did not perform well. There was some success in South Korea for the first 20 days after implementation of social distancing, but the rates rose sharply afterwards.

Digital contact tracing (DCT)

DCT data were extracted and analyzed for 15 countries/regions from 31 sources ([Supplementary eTable 2](#)). The average adoption rate in the studied countries was 37.6%. As shown in [Fig. 1](#), centralized DCT performed better than decentralized apps (detailed data are presented in [Supplementary eTable 4](#)). Logistic regression showed that countries with centralized DCT (OR:0.25 [95% CI: 0.02,2.06]), higher adoption rates (1.016 [0.0002, 1.06]) and policy enforcement (0.63 [0.06, 2.37]) were more likely to have better control. Policy enforcement in Hong Kong, South Korea, and Singapore included monetary fines upon those who violated DCT reporting guidelines.

[Fig. 2](#) shows the trends in the number of cases 30 days before and after the DCT implementation. Except Singapore ($+188\%$), centralized DCT apps in all studied countries substantially decelerated the spread of the COVID-19. The decreases in rates were substantial: Australia (percent change, -86%), South Korea (-85%), and China (-30%). In other countries, the number of new cases showed a

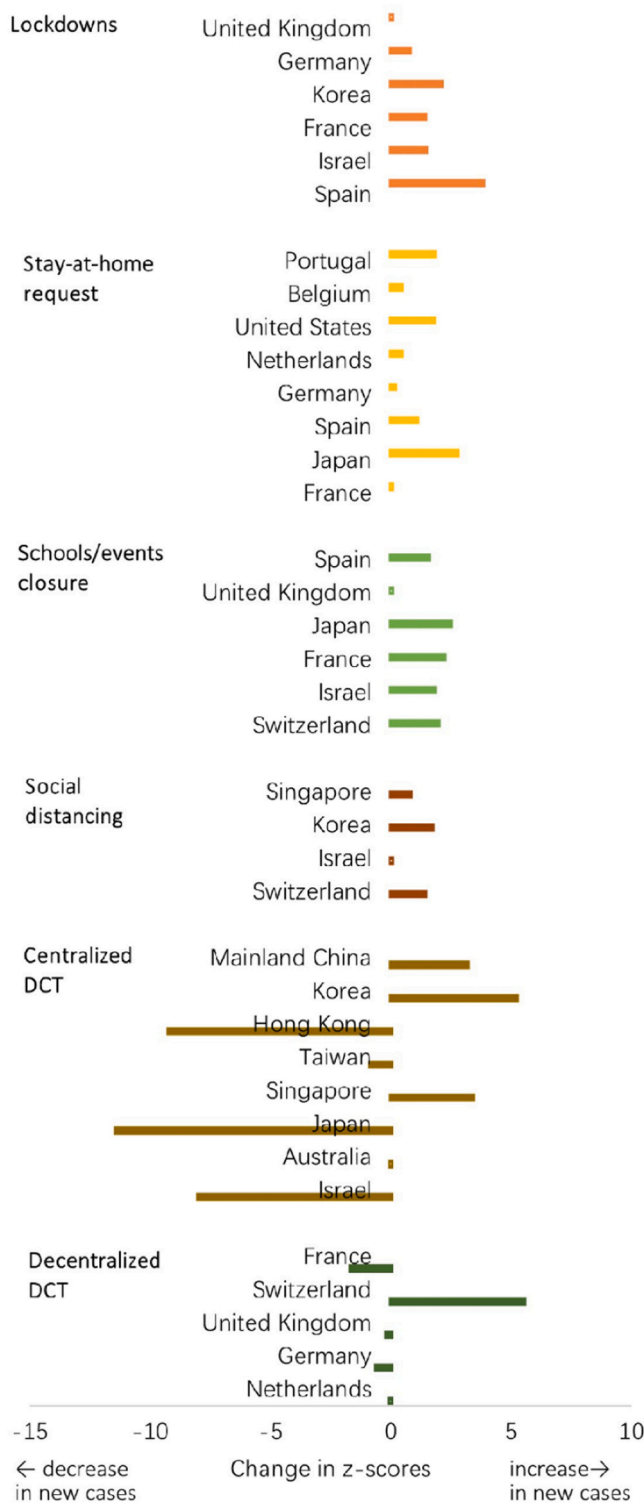


Fig. 1. Effectiveness of COVID-19 containment measures. Negative values indicate a decrease in the number of new cases over 30 days after deployment of containment measure compared to 30 days prior to implementation. Data from the first half of 2020. Abbreviations: DCT, digital contact tracing.

decreasing trend after DCT launch (i.e., Hong Kong [$z = -5.5$] and Japan [$z = -6.14$]). No major trends could be discerned in Israel and Taiwan. In decentralized DCT rollouts, the number of new cases increased significantly after the launch in France (+178%), the United Kingdom (+361%) and Netherland (+198%). A downward trend was observed in Germany and Estonia.

Discussion

In spite of mass vaccination campaigns against COVID-19 in most countries, the control of pandemic remains frustratingly difficult to achieve. As we start the third year into the pandemic, some countries have started to ease the pandemic restrictions, whilst others such as China (Shanghai) have once again started to enforce lockdowns and closures. However, the effectiveness of these measures has been questioned [21,25–27]. It is likely that the effectiveness is dependent on a number of cofactors, including, type of containment measure, the degree of enforcement, public attitude and acceptance, extent of infection in the population, and the degree of testing [21,28–31]. Modeling studies have indicated the importance of early implementation of restrictions; delays as little as a few weeks after an outbreak can have an unrecoverable impact on viral transmission [31,32]. The findings from this study reveal that conventional control strategies such as lockdowns, stay at home requests and school closures could not completely stop the transmission chain of SARS-CoV-2 in most of the countries studied. Typically, such containment policies should lead to better control, but in real-world settings, they did not perform as expected. Poor enforcement and public acceptance of these measures is most likely to be an important contributing factor [33]. By contrast, centralized DCT was associated with a decline in the number of new cases.

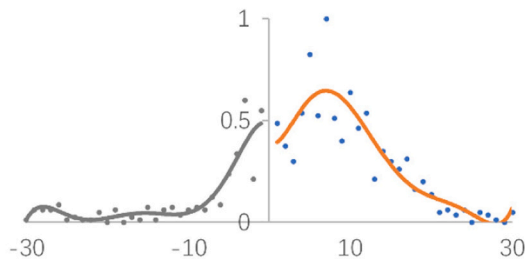
Several studies have demonstrated that government interventions can potentially reduce the peak number of COVID-19 cases [15,34,35]. However, the timing of implementation and duration will influence the outcome [31,32]. Other studies have echoed the ineffectiveness of physical measures by assessing the impact of full lockdown strategies applied in some western countries [25,26]. These reports found no evidence of any discontinuity in the growth rate, and reproduction estimate trends after deploying full lockdown strategies. Results from a study of European countries revealed that the COVID-19 epidemic can rebound when control measures are relaxed [36]. One possible reason could be the fact that compliance with population movement restrictions is difficult to sustain economically and socially [1,19].

DCT systems were effective in curtailing the spread of the SARS-CoV-2 virus. These apps can be integrated into comprehensive control strategies [22,23,37]. DCT augments conventional public health strategies and is not considered a replacement for social measures. Effectiveness of DCT is enhanced when measures are implemented in a centralized and enforced manner [23,24]. For instance, South Korea, China, and Japan had successfully used centralized DCT apps to control the spread of COVID-19. Arguably, this involves placing public interest above individuals' right to privacy [38–40]. The legal basis and data governance structure for accessing and managing personal medical information during a public health crisis was encountered during the 2002 SARS and 2014 MERS coronavirus outbreaks [41,42]. It was apparent that tracing the movement of infected and exposed individuals is crucial. Despite initial enthusiasm for this approach in North America and Europe, privacy concerns and technical issues hampered the enforcement of centralized DCT [43,44]. Integrating DCT and conventional measures cannot only leverage the advantages of the two approaches but also help flag exposures and identify asymptomatic infected individuals. DCT entails trade-offs between public health protection and individual privacy [45]. Continued technical improvement may further increase efficacy, particularly across regional borders. Several factors hinder the uptake of DCT apps, these include privacy concerns, lack of trust, and suboptimal interface design [46,47].

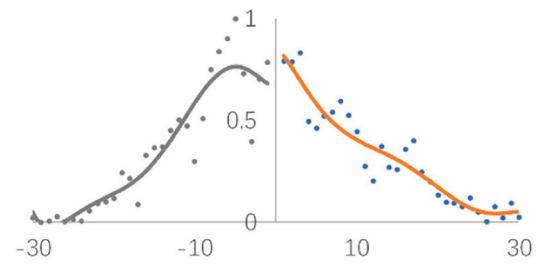
As lockdowns and border restrictions did not stop the spread of COVID-19, there is a need for better guidance on the number of exposed contacts who need to be isolated. Previous studies about the number of close contacts vary significantly, from a few to more than 80 [35,48]. It is unrealistic to quarantine the whole

Centralized DCT

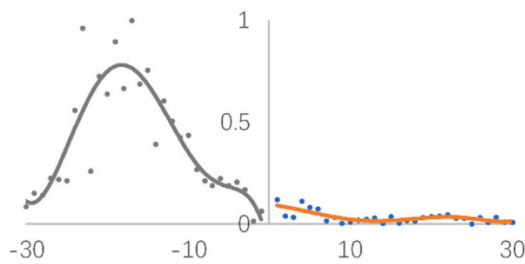
Hong Kong



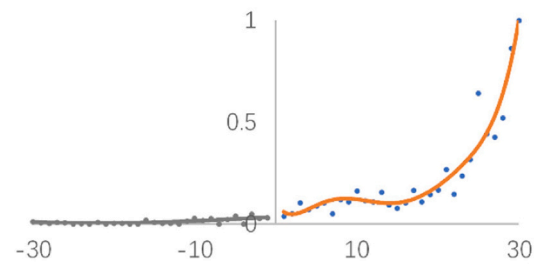
Japan



Australia

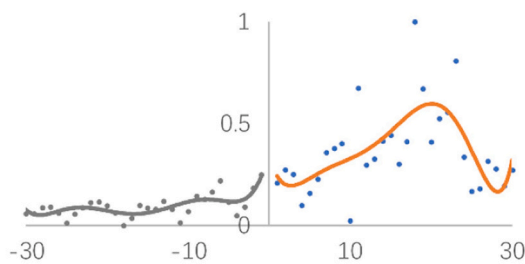


Singapore

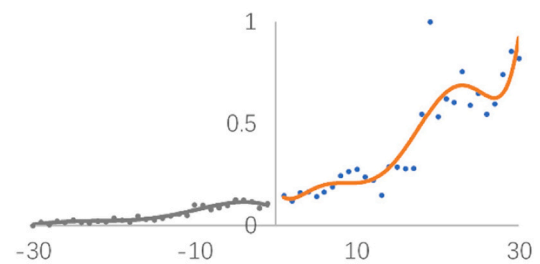


Decentralized DCT

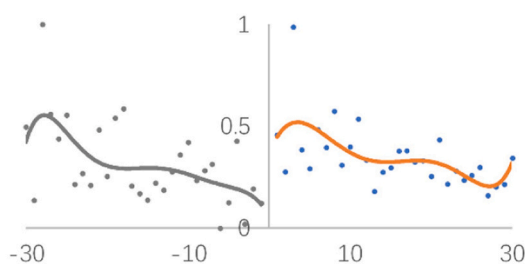
France



United Kingdom



Germany



Switzerland

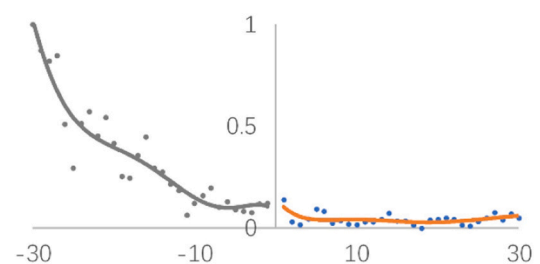


Fig. 2. Comparison of centralized versus decentralized digital contact tracing (DCT). Confirmed new cases in selected countries for 30 days before and after implementation of digital contact tracing (DCT) in 2020. Horizontal (x-axis) indicates the number of days. Vertical (y-axis) shows standardized new case rates.

population, as suggested in the case of Wuhan province. Our results also suggest that intercity and international travel closure could not effectively retard the spread of the virus. Virus spread continued after intercity lockdowns due to difficulties in tracking and validating travel information of returning domestic or international travelers [25,49]. Citizens inside lockdown cities going out without maintaining social distancing, and people outside

entering the cities could not be accurately tracked. In South Korea, the initial success of implementing social distancing measures broke down after the first 20 days, which highlights the need to trace the source of infection for targeted containment. Hence, the critical role of DCT in countries such as Japan, in switching the trend from increasing to decreasing number of new cases, as shown in our results.

Limitations

Like any study of this nature, our study has a number of limitations. Country level data are subject to generalizations that can lead to ecological bias. Large countries such as China and the US are not homogenous in terms of policy implementation and case reporting. The first half of 2020 was a time of changes in policy and rapid deployment of preventive measures. Thus, cross effects of measures applied sequentially could contaminate our before-after data. The initial intense phase of COVID-19 was also characterized by lack of systemic reporting, changes in case definitions, and variable extent of enforcement of each containment measure. Thus, temporal patterns need to be interpreted cautiously. Despite these limitations, the study findings reflect real-world outcomes of public health measures, and hence the true limitations of using these measures to control a highly transmissible respiratory virus. These findings also reflect the reluctance of the public to respect these restrictions and to avoid circumventing protective measures for personal expediency.

Conclusion

Conventional containment measures widely implemented in the early outbreak of COVID-19 were not sufficient to prevent the spread of the virus in most countries. However, strict enforcement of these strategies, combined with centralized DCT appears to be more effective. This approach, if implemented early in an outbreak, could contain and prevent spread beyond the epicenter.

Ethics approval and consent to participate

Ethics approval was not required for this research as this study does not involve human participants or animal subjects.

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CRedit authorship contribution statement

All authors had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis. Dr Jiang, Deng, Zeng, Lin, Lee verified the data. **Ka Kit Leung:** Investigation, Methodology, Project administration, Writing – review & editing. **Rusheng Zhang:** Investigation, Methodology, Writing – original draft, Writing – review & editing. **Muhammad Jawad Hashim:** Investigation, Writing – original draft, Writing – review & editing. **Mingying Fang:** Investigation, Methodology, Writing – original draft, Writing – review & editing. **Jing Xu:** Investigation, Methodology, Writing – original draft, Writing – review & editing. **Derek Sun:** Investigation, Writing – review & editing. **Xiang Li:** Investigation, Writing – review & editing. **Yanhui Liu:** Project administration. **Haohui Deng:** Project administration. **Dingyuan Zeng:** Project administration. **Zhong Lin:** Project administration. **Peiqing He:** Investigation. **Yu Zhang:** Investigation. **Xuehong Zhu:** Investigation. **Shui-Shan Lee:** Investigation, Project administration, Supervision, Writing – review & editing. **Ziad A. Memish:** Writing – review & editing. **Guozhi Jiang:** Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. **Gulfaraz Khan:** Investigation, Writing – original draft, Writing – review & editing.

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Competing interests

The authors declare no conflict of interest.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:[10.1016/j.jiph.2022.04.012](https://doi.org/10.1016/j.jiph.2022.04.012).

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