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The impact of COVID-19 vaccination campaign in Hong Kong SAR China and Singapore

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ABSTRACT

Background: Vaccination has been the most important measure to mitigate the COVID-19 pandemic. The vaccination coverage was relatively low in Hong Kong Special Administrative Region China, compared to Singapore, in early 2022. Hypothetically, if the two regions, Hong Kong (HK) and Singapore (SG), swap their vaccination coverage rate, what outcome would occur?

Method: We adopt the Susceptible – Vaccinated – Exposed – Infectious – Hospitalized – Death - Recovered model with a time-varying transmission rate and fit the model to weekly reported COVID-19 deaths (the data up to 2022 Nov 4) in HK and SG using R package POMP. After we obtain a reasonable fitting, we rerun our model with the estimated parameter values and swap the vaccination rates between HK and SG to explore what would happen.

Results: Our model fits the data well. The reconstructed transmission rate was higher in HK than in SG in 2022. With a higher vaccination rate as in SG, the death total reported in HK would decrease by 37.5% and the timing of the peak would delay by 3 weeks. With a lower vaccination rate as in HK, the death total reported in SG would increase to 5.5-fold high with a peak 6 weeks earlier than the actual during the Delta variant period.

Conclusions: Vaccination rate changes in HK and SG may lead to very different outcomes. This is likely due that the estimated transmission rates were very different in HK and SG which reflect the different control policies and dominant variants. Because of strong control measures, HK avoided large-scale community transmission of the Delta variant. Given the high breakthrough infection rate and transmission rate of the Omicron variant, increasing the vaccination rate in HK will likely yield a mild (but significant) contribution in terms of lives saved. While in SG, lower vaccination coverage to the level of HK will be disastrous.

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1. Introduction

Severe acute respiratory syndrome coronavirus (SARS-CoV-2), the etiological agent of coronavirus disease 2019 (COVID-19), has continuously spread and evolved for nearly three years since its outbreak at the end of 2019 (Huang et al., 2020). On March 11, 2020, WHO declared COVID-19 a pandemic (World Health Organization, 2020).

The Omicron variant was first reported in South Africa on November 24, 2021, and later supplanted the Delta variant as the predominant SARS-CoV-2 variant globally (Nyberg et al., 2022; Wolter et al., 2022). In South Africa and the UK, the Omicron variant causes less severe disease for the individual than the Delta variant. However, during the widespread outbreak, the impact of deadly infections on the population is still substantial (Thompson et al., 2022; Wolter et al., 2022). More than 30 spike protein amino acid mutations are present in the Omicron variant, which increased its transmissibility, severity, and immune escape ability (Callaway, 2021). On November 26, 2021, WHO classified it as the fifth variant of concern (VOC) (World Health Organization, 2020). The growing number of cases and sequencing data indicate that Omicron VOC is highly contagious, spreading more quickly than any prior variant and infecting three to six times as many people at the same time as the Delta variant (Callaway, 2021). Omicron cases account for 99% of all new COVID-19 cases at the beginning of January 2022 in the UK (UK Health Security Agency, 2022).

Before the outbreak of the Omicron variant, Hong Kong SAR China (HK, population 7.4 million) began implementing comprehensive strategies to contain COVID-19, including social distancing measures, restrictions on entry at borders, isolation of cases, quarantine of close contacts, and use of personal protections (Cowling et al., 2020). These strategies successfully reduced the spread of SARS-CoV-2. As of February 1, 2022, the total number of confirmed cases in Hong Kong was 14,326, accounting for only 0.8% of the current total number of infected people (Our World In Data, 2022). However, the Omicron variant triggered a new infection wave in Hong Kong despite Hong Kong's stringent prevention strategies. When the first Omicron case was detected on December 27, 2021 (Government News, 2022), Hong Kong immediately tightened various social distancing measures to avoid the outbreak of Omicron, but it was still too late. From February 1 to April 1, 2022, the accumulative number of new cases in Hong Kong increased to 1.16 million in just 60 days. This was due to the Omicron's high infectivity, short transmission circle (2–3 days), as well as its strong capability of vaccine breakthrough (Kupferschmidt & Vogel, 2021). Even though more than 62.5% of Hong Kong residents had received at least two doses of the COVID-19 vaccine by December 31, 2021 (Our World In Data, 2022), it may not sufficient to stop the spread of the Omicron variant.

Singapore (SG), a Southeast Asian Island nation with a population of 5.5 million, was frequently used to compare with HK in their responses to COVID-19. From early 2020 to September 2021, a stringent COVID-19 suppression plan was implemented in SG (Ng et al., 2022). Fully vaccinated (two doses) accounted for 86.3% of the total population by December 31, 2021. Both HK and SG approved SINOVAC and BioNTech as two vaccine options. As of March 1, 2022, 90.5% of the total population received full vaccination, with 67.6% receiving a booster dose (Our World In Data, 2022; WHO. Singapore Situation., 2022). After the Delta wave in December 2021, a large wave dominated by the Omicron variant broke out, peaking from late February to early March 2022 despite high vaccination coverage (WHO. Singapore Situation., 2022).

The fifth wave of COVID-19 pandemic in Hong Kong, starting from Dec 31, 2021 to date, resulted in a total of 10,041 fatalities and 1.8 million infections, majority of which were caused by Omicron. On March 7, 2022, the 7-day moving average case fatality ratio (CFR) of COVID-19 in Hong Kong reached a record high of 2.9% (Hong Kong government website, 2022). During the same time period, 1.7 million new cases were reported in Singapore with only a total of 807 deaths recorded (Our World In Data, 2022).

We speculate that the disparate levels of vaccination coverage can partly explain the striking differences in fatality rates of COVID-19 between Hong Kong and Singapore. Studies showed that the vaccine provides a protective effect against Omicron infection and can significantly reduce the severity and fatality rate of the disease (McMenamin et al., 2022). At the outset of the Omicron outbreak, on December 31, 2021, Singapore had almost 86% of its population fully vaccinated, whereas Hong Kong had only 62%; the rate of people who receive booster doses in Singapore reached 40%, whereas the rate was barely 5% in Hong Kong (Fig. 1). Therefore, this study aims to simulate the COVID-19 pandemic in Hong Kong and Singapore using the

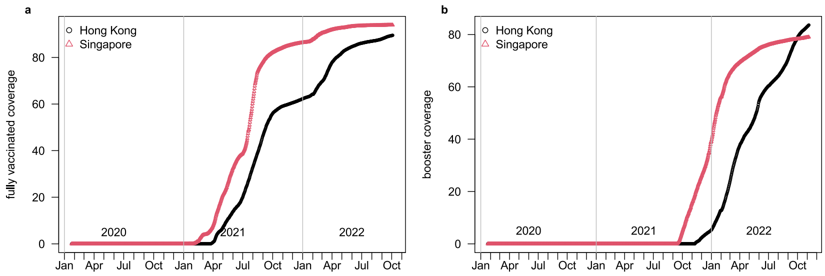

Fig. 1. Vaccination coverage (the second dose in panel a and the third dose in panel b) in Hong Kong and Singapore. Panel a: fully vaccinated per 100 people over time. Panel b: the third dose (booster) delivered per 100 people over time. Black circles denote HK while red triangles denote SG. We assume the third dose delivered per 100 people should be close to the people received the third dose per 100 people.

Susceptible-Infectious-Recovered type model in order to examine the effect of vaccination coverage on the death rate of the Omicron variant. Our study period is from the beginning of the pandemic to November 4, 2022. A comparison of the characteristics of the two regions is given in Table S1 in the supplementary material. Figs. S1 and S2 in supplementary material show the raw case-fatality rate (reported death toll divided by reported case total in a time window) over time for the two locations, and the proportion of variants in the two locations, respectively.

2. Method

We adopted an $S - S_V - E - I - H - D - R$ model from (Chen et al., 2022) (see Fig. 2) and fitted the model to the weekly COVID-19 deaths (the data) in Hong Kong and Singapore via the state-of-the-art R package POMP (King, 2017). The population is divided into susceptible (S), vaccinated (S_V), exposed (E), infectious (I), hospitalized/severe cases (H), recovered/immunized (R), and death (D) classes, respectively. The characteristic of this model is that it simulates multiple Omicron subvariants invaded and caused multiple population-level immune escapes. Using standard and widely used likelihood-based inference R software packages, we fit our model to weekly deaths, while taking into account the number of daily fully vaccinated and daily booster doses delivered. We assumed all other factors, including disease control measures were synthesized into the time-varying transmission rate. We assumed immune escapes caused a sudden shift of the proportion recovered and vaccinated to the susceptible pool. We assume such immune evasion occurred twice due to the invasion of the multiple subvariants: the first evasion by BA.1 and BA.2 (on January 10, 2022), while the second evasion by BA.4 and BA.5 (on May 26, 2022). We assume the proportion of immunized who lose immune is between 20% and 30%. We assume the infection fatality rate dropped by a ratio r in 109 days after the first invasion and $r \in [40\%, 60\%]$.

We omit the model equations in this work since they were given in previous works (Chen et al., 2022) and supplementary material. Vaccination rates (second dose/fully vaccinated and third dose/booster) are calculated based on data (Hannah Ritchie, 2020), after processing (ie, converting from per capita to per unvaccinated) as described in (Feng et al., 2022). We assume $\psi = 0.2$ per year. Note that this parameter controls the rate of loss of immunity against both reinfection and reinfection-led death, since we did not distinguish the original susceptible and the “new” susceptible due to loss of immunity. We will discuss this point later. We assume $\epsilon = 0.15$, which means an initial protection rate of 85% against death after vaccination (second dose). The initial protection rate of the booster is assumed at 100%. These two rates decay at a rate $\psi = 0.2$ per year. The infection fatality ratio (IFR) equals ϕ^2. We used exponential cubic spline in the transmission rate $\beta(t)$, we used 12 nodes in the period before the Omicron invasion and 6 nodes after the invasion. This technique setting has been used in previous publications (Feng et al., 2022; He et al., 2022).

After we achieved a successful fitting using the actual vaccination rate, in particular we reconstructed the transmission rate and the magnitude of immune escape of Omicron, we re-ran our model under the scenario that the vaccination implementations (including daily fully vaccinated and daily booster delivered) were switched between HK and SG. We compared the death total and peak timing under this hypothetical scenario with the actual epidemic situation. All data used in our model are from Our World In Data (Our World In Data, 2022). We uploaded our data and code in (Boyu, 2022). Readers who are interested in the detail of the model equations and methodology may access our code in (Boyu, 2022).

3. Results

The fittings for HK and SG are shown in Fig. 3a&b. We estimate that the twice immune evasions caused 22% and 20% immunized (recovered and vaccinated) shift to susceptible in HK, respectively. The two numbers are 20% and 30% in SG. The estimated IFR is 0.289% in HK and 0.225% in SG, and dropped to 0.15% and 0.12%, respectively.

The weekly reported cases (red circle) in Hong Kong and Singapore are mostly within the shaded range (95% range of 1000 simulaitions), indicating that the data fittings for HK and Singapore are good. According to previous studies, the surge of Omicron subvariants such as BA.2, BA.2.12, BA.4, and BA.5 may have contributed to the death in the new wave of the

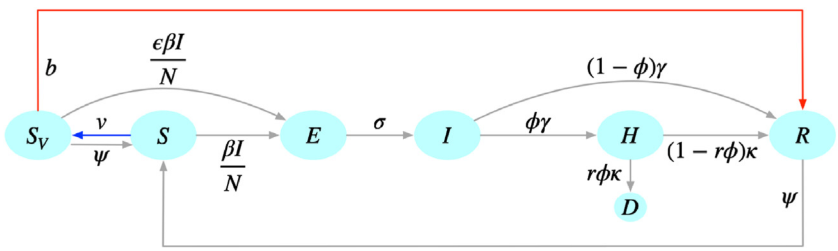

Fig. 2. The flow chart of $S - S_V - E - I - H - D - R$ model. The model equations are given in previous work (Chen et al., 2022) and supplementary material. The population is divided into seven compartments. The rates at which individuals move from one compartment to the next compartments are shown beside the arrows. The rate ψ controls immunized individuals losing protection against reinfection or breakthrough infection and deaths. The ν and b denote the vaccination rates, second dose and third dose, respectively.

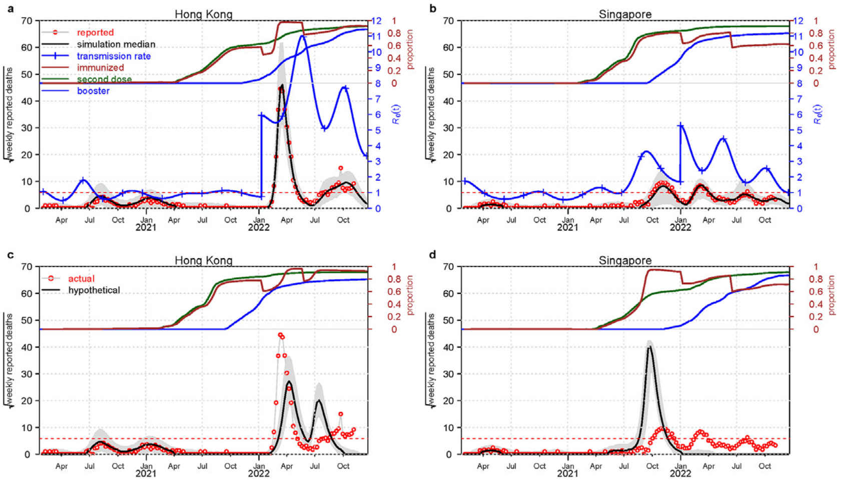

Fig. 3. Comparison of actual and hypothetical scenarios (when vaccination rates were swapped). Panels (a,c) for HK. Panels (b,d) for SG. Red circles and black curves represented reported COVID-19 deaths and simulated COVID-19 deaths. Blue curves with crosses showed the reconstructed transmission rates. The green and blue curves show the daily fully vaccinated per 100 persons and the boosters delivered per 100 persons. Panel (c,d) showed the comparison of actual and hypothetical weekly deaths under the actual vaccination data vs. under the hypothetical scenarios. A replica of this figure in normal scale instead of square root is given in Fig. S3.

pandemic in 2022. We model the invasion of these subvariants by shifting a proportion of recovered and vaccinated to the susceptible pool.

The deaths in Hong Kong after the switch of vaccination coverage rates with SG are depicted in Fig. 3c. If the vaccination coverage in SG were applied in Hong Kong i.e., 86% full vaccination coverage rate and 40% booster dose coverage before the invasion of Omicron, the death total reported in HK would decrease by 37.5% and the timing of the peak would delay by 3 weeks. The summary of the observed total deaths, the model simulated total deaths under the actual scenario and the hypothetical scenario are given in Table 1.

Fig. 3d represents the result in Singapore after the switch of vaccination coverage rates with HK. It demonstrated that when confronted with the initial wave of the Delta variant epidemic, the mortality rate was significantly higher than the actual level. The death total reported in SG would increase to 5.5-fold high with a peak 6-week earlier than the actual during the Delta variant period, ushering in the greatest outbreak since Singapore was affected by the epidemic.

4. Discussion and conclusion

We simulated the epidemic trends of COVID-19 in Hong Kong and Singapore using an SEIR-based model. We then switched the vaccination coverage rates between the two regions throughout the same period. The result showed that even if vaccination coverage in Hong Kong could be as high as that in Singapore, it was difficult to avoid the peak of the mortality rate, which was postponed by 3 weeks with a 37.5% reduction in total deaths when compared to the actual situation. Meanwhile, lower vaccination coverage in Singapore would result in a peak of the death from the Delta variant and avoid the subsequent Omicron outbreak.

Hong Kong and Singapore are two regions whose development is highly comparable (Table S1 in supplementary material). Hong Kong's economic freedom was ranked 1st in the world in 2022, followed by Singapore (Fraser Institute, 2022). In addition, the population density of Singapore is slightly higher than that of Hong Kong, with 7688 and 6810 people per square kilometer, respectively. However, Hong Kong has a higher proportion of elderly people than Singapore. The proportion of people aged 65 and above was 20.9% and 16.6% in Hong Kong and Singapore respectively while the proportion of those aged 80 years and above was 5.4% and 4% accordingly (Census and Statistics Department, 2022; Department of Statistics, 2022). With a higher population density and a comparable level of economic development, Singapore's younger population structure may be one of the important factors contributing to the lower COVID-19 mortality rate.

Table 1
Summary of the observed total deaths, the model simulated total deaths under the actual scenario and the hypothetical scenario (from the beginning of the pandemic to Nov 4, 2022).

	Observed	Actual	Hypothetical
HK	10470.0	10483.5	6547.5
SG	1687.0	1507.0	8256.5

It is estimated that vaccinations prevented 14.4 million deaths from COVID-19 around the world in 2021 (Watson et al., 2022). By the end of Dec 2021, 64% of the vaccine-eligible persons received at least 2 doses in Hong Kong, but the rates were lower among the elderly: 2-dose coverage was 45% among those aged 70–79 years and 18% among those aged 80+ years. Previous analysis showed 67% of the deaths reported in Hong Kong during the 5th wave of the pandemic occurred in unvaccinated persons aged 60+ years (Smith et al., 2022). The analysis showed the relative risk of dying from COVID-19 among unvaccinated persons in Hong Kong was 33.2 times the risk among persons who received at least 2 doses. Our simulation, similar to the analysis, showed that by applying the high vaccination coverage rate seen in Singapore to Hong Kong, the death rate in Hong Kong could be reduced temporarily. Vaccination seems to be effective in preventing death from the Omicron variant. Increasing COVID-19 vaccination coverage among all population groups (in particular the high-risk groups) remains one of the most important public health measures in mitigating the pandemic.

Our simulation, on the other hand, explicated that COVID-19 vaccines alone may not avert the death toll. Even with a vaccination coverage and booster dose coverage as high as that in Singapore, Hong Kong would still experience a peak of mortality rate in the 5th save of the pandemic caused by Omicron as shown by our model. The time to peak, however, would be lagged by 3 weeks with a 37.5% reduction in total deaths. Infections are reported in fully vaccinated individuals (Bergwerk et al., 2021; Brown et al., 2021), and antibody level decreases over time (Lin et al., 2022). Higher coverage of full vaccine and booster dose might be needed to further reduce the deaths from Omicron subvariants. However, as shown by previous studies (McMenamin et al., 2022), vaccines can prevent serious infection but not necessarily the transmission of SARS-CoV-2. The non-pharmaceutical interventions to contain the spread of the virus that the global population has by now become accustomed to will need to remain in place for a while longer.

Our study has several limitations. Firstly, we simply modeled the aggregated death and not the specific infection process, hence we did not distinguish between the infection fatality rates (IFR) of breakthrough infection (BTI) and unvaccinated infection. In this model, we assumed that there was a unified IFR. Due to the fact that the IFR of BTI is significantly lower than that of unvaccinated infection, we have increased the vaccine effectiveness to BTI in order to achieve a balance, i.e., we have increased the initial vaccine effectiveness so that our simulated situation has fewer BTI than reality and the final deaths of BTI are similar to reality. If we explicitly model BTI and unvaccinated, a more realistic model may be developed. Secondly, our model did not take into account the age-specific deaths and vaccination rate. Ideally one should build an age-structured model. Due to the data availability, the non-age-structure model is used in our simulation because of its simplicity. In the future, we will apply our non-age-structure model to the age-structure one. Thirdly, we did not include all Omicron subvariants such as BA.2, BA.2.12, BA.4, and BA.5 into the simulation model. But it did not seem to have a significant impact on the data fitting. Fourthly, our model mainly focused on the impact of vaccination on the death rates, thus impact from other risk factors including non-pharmaceutical interventions and individual-level comorbidities could not be examined. Last but not least, vaccine effectiveness might be varied by type, which was not taken into account in our simulation.

Omicron has taken Hong Kong from having one of the lowest COVID-19 death rates in the world to having the highest daily death rate per capita. Our model showed that the low vaccine rate partly contributed to the high death rate, but vaccination alone seems not sufficient to stop the transmission of Omicron subvariants. Booster doses and non-pharmacological interventions might still be needed to curb the pandemic.

Ethics approval and consent to participate

The ethical approval and individual consents were exempted as the aggregated data were used in this study.

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Author contributions

All authors conceived and conducted the research and wrote the draft. All authors critically revised the manuscript, and all authors approved the submission.

Data and materials availability

Data are publicly available online. Data and code are available at: https://www.zotero.org/groups/4876337/boyu_yu.

Declaration of competing interest

All authors declared no competing interests. The funding agencies had no role in the design and conduct of the study; collection, management, analysis, and interpretation of the data; preparation, review, or approval of the manuscript; or decision to submit the manuscript for publication.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.idm.2022.12.004.

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