

Herd immunity of Covid 19 in dynamic environments with vaccination: a model based study

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Herd immunity of Covid-19 in dynamic environments with vaccination: a model-based study

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Abstract

Background

The first wave of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) in Canada is entering the last stage, while the development of vaccine is still ongoing. A thorough analysis on the potential effect of restoring to the normal life was needed.

Methods

We used an infectious disease model which optimized for individual immunity to investigate the potential impact of the vaccine on the number of cases, \mathcal{R}_t , and the duration of the epidemic. We modeled the severity of the cases with three intervention measures and the effect of herd immunity. The combined intervention strategies with the vaccination, speed of vaccination, and the proportion of population pre-vaccinated before reopening were modeled to give an overview of the effect of the vaccination. For each simulation, we set the observation range to be from Feb, 2020 to Oct. 2021, and modeled the number of cases after the first wave, the change of reproduction number (\mathcal{R}_t), and the proportion of immunized population under the effect of waning immunity.

Findings

We found the proportion of immunized population to reach herd immunity in a dynamic environment to be between $1 - \frac{1}{\mathcal{R}_0}$ and $1 - \frac{1}{\mathcal{R}_0^2}$; for Covid-19, the threshold proportion is 64.16%, the final proportion of infections could be up to 87.15% when basic reproduction number (\mathcal{R}_0) is 2.79. The average number of cases predicted in Canada after the first wave was 285590, 90260, 163057, and 60082 with no intervention, social distancing, quarantining severe cases, and combined strategies; 122261, 89903, 49276, 39856, and 10983 cases with 0.1%, 0.2%, 0.3%, 0.4%, and 1.0% of the population vaccinated per day; 117475, 93502, 91634, 79418, and 8713 cases with 10%, 20%, 30%, 40%, and 50% of population immunized before

reopening. Assuming the half-life of the effectivity of the antibody is 48 weeks for symptomatic cases, 24 weeks for asymptomatic cases.

Interpretation

Neither of these strategies cannot prevent the second wave solely nor together. However, the third wave can be prevented with both social distancing and quarantining severe cases in practice. The speed and timing of vaccination has a direct impact on the reduction of the final number of cases. Unexpectedly, the proportion of population immunized before reopening did not lead to a huge shift of the number of cases after the first wave when the immunized proportion is lower than the critical proportion (49.6%) when social distancing is in practice.

Funding

None.

Introduction

Novel coronavirus pneumonia is an acute infectious disease that transmits rapidly from person to person. The initial symptoms of the virus are fatigue, fever, dry cough, and dyspnea.¹ Most patients can develop antibody and cure without medical intervention; however, 19.1% patients with severe symptoms may develop acute respiratory distress syndrome, which may lead to death.² Soon after it was detected in late December 2019, from Wuhan, China, the number of cases grew exponentially worldwide and became a global pandemic.³ As the development of the vaccine proceeding, a thorough study on the effect of the vaccine on the virus containment and economy reopening was needed.⁴ Herd immunity can be reached by vaccinating a huge proportion of the population to protect both vaccinated and unvaccinated population.⁵ Immunity of a virus can be gained through both getting infected and vaccinated, we created a model to better describe the immunity within a population and an individual.

Research in context

Evidence before this study

“Herd immunity strategy” and criticized by the mainstream scientists since proposed. However, to mitigate the virus transmission, herd immunity needs to be reached through vaccine. As the vaccine development proceeding, a study about the effect of the vaccine on the future containment of the virus. The mixed non-medical and medical approach to the final elimination of the virus was required.

Added value of this study

The study used a SEIR model optimized for individual and population level immunity, investigated how the vaccination with non-medical interventions, speed of vaccination, proportion pre-vaccinated before reopening could affect the number of cases after the first wave. Assuming a waning immunity, we also estimated how long could the epidemic last with the effect of vaccination in Canada.

Implications of all the available evidence

Our result suggests the importance of non-medical intervention even with the presence of medical vaccine to bring down the number of cases. The speed of vaccination was determined to be a more important role than the pre-immunized proportion before reopening, indicating the feasibility and efficiency of reopen paralleled with vaccination. The pre-immunized population would not contribute to a significant decrease in the number of cases if the proportion is below a certain threshold. The epidemic is predicted to last as long as 2 years in Canada.

We focused on the effect of vaccination on the overall severity of the epidemic and aimed to provide an overview the effect of speed of vaccination, reopening with different vaccination levels, and different

approaches achieving the herd immunity. Based on our model, we predicated and evaluated the different scenarios and gave specific suggestion for Canada as well as other countries considering reopen.

Method

Model

Immunity and transmission

To better describe and quantify virus transmission, we brought the model to an individual level. The individuals are defined as socially independent units, with his/her age following the age distribution in the modeling region. The people contact per day per individual is given by a randomizer algorithm, assuming same possibility of transmitting the virus (for individual without immunity). We defined “effective contact”, which is the contact between a patient that is able to transmit the virus and an unimmunized individual that may lead to a success infection. The effective contacts made per day per patient would vary depend on the intervention and overall herd immunity within the population. Without any intervention, the \mathcal{R}_0 was predicted to be 2.79, according to Liu and colleagues.⁶ We assumed a same possibility of transmission of each effective contact remains the same without intervention (herd immunity within a population would not affect the possibility of transmission of each effective contact, it will only decrease the number of effective contacts made per patient).

We assumed an average incubation period of 4.5 days, during the incubation period, the preclinical infection period lasts an average of 2 days, the patient would be infectious until 5 days since he/she shows the symptom.^{7,8} Each symptomatic patient has a possibility of 19.1% of becoming a severe case. The severe case has a higher risk of death, as well as the possibility to being quarantined depending on the intervention strategy taken.⁹

The IgG levels and neutralizing antibodies in a high proportion of individuals who recovered from SARS-CoV-2 infection start to decrease within 2–3 months after infection, approximately 12% of the cases who recovered tested negative for the antibody.¹⁰ To better describe this phenomenon, we quantified the immunity of each individual in the population. We assumed 100% efficacy and effectiveness of antibody induced by the virus and vaccine, and the immunity gained by an individual would preserve at 100% within 8 weeks after immunization. After this, an exponential decay of pattern the effectiveness of the vaccine/antibody with half life of 48 weeks (the effectiveness would decay to its half each 48 weeks) was described in the model.

We assumed that 17.9% of the cases are asymptomatic, which has 65% of the ability of virus transmission than those have symptom (this will not affect the overall \mathcal{R}_0). Immunity of asymptomatic cases was assumed to decay twice as fast as the symptomatic cases (the half life is 24 weeks).^{10,11,12}

Intervention Scenarios

We introduced three different virus-mitigating strategies: social distancing, quarantining severe cases, and city lockdown (which would in effect only when triggered). Each of these control measures has individual and social level of impact in order to simulate the actual scenario.

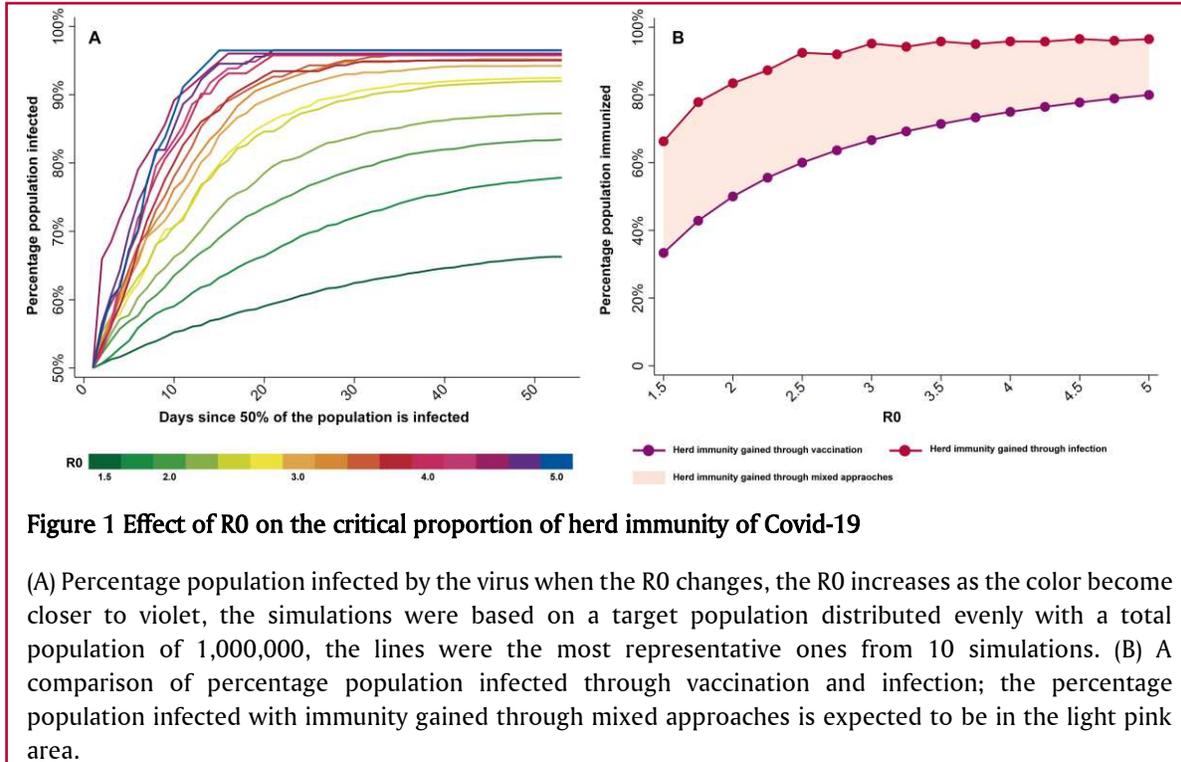
For social distancing, since people are intentionally wearing PPE and staying apart, we assumed the overall effective contacts made per day per person would be cut by half (50% of the control group). Quarantining severe cases includes hospital-quarantining and self-isolation: hospital-quarantining means the severe cases were quarantined, so they are less likely to transmit the virus (assuming 90% of contacts made are nullified), while the self-isolation means that the symptomatic cases would self-isolate to intentionally reduce his/her ability to transmit the virus, thus they make 70% less contacts than asymptomatic cases and exposed cases.¹³

Observation range

On January 26, 2020, the first case of coronavirus was discovered in Canada, the number of cases then started to increase exponentially.^{14,15} To make it more visually comfortable, we picked February 1, 2020 to be the start of the x-axis, and the end to be September, 24th 2021, with a full observation range of 600 days.

Results

Herd immunity gained through various approaches



A positive relationship between final proportion of population infected and the \mathcal{R}_0 of the virus is observed. However, the critical value when the immunity is gained through infection is higher than the minimum threshold proportion found in the previous studies in a static case.¹⁶

The observed final proportion of infected population for the virus with a certain \mathcal{R}_0 in a dynamic environment (the red line) is higher than the theoretical threshold proportion in the static environment (the purple line) (Figure 1). However, in the actual scenario, the final infected proportion of population may vary depends on the ratio of the immunity gained through infection and immunity gained through vaccination within the immunized population, and the intervention strategies which changes the \mathcal{R}_t . The upper (average theoretical value in a large, static, and evenly distributed population) and lower limit for P_{cr} , P_{crv} (critical proportion of herd immunity gained through infection) and P_{crv} (threshold proportion of herd immunity gained through vaccination) is:

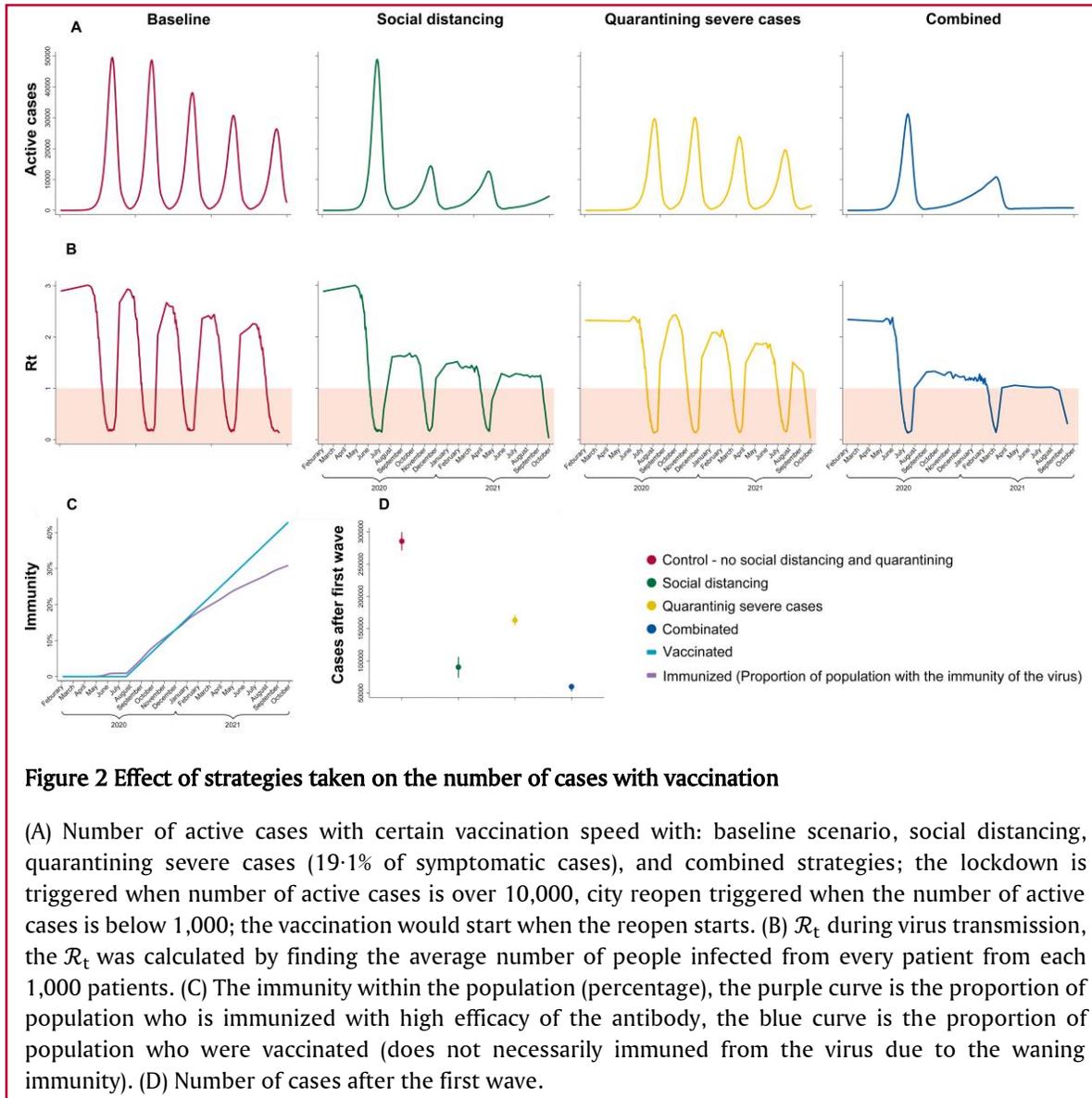
$$\begin{aligned}
 P_{cr} &= 1 - \frac{1}{\mathcal{R}_0^2} \\
 P_{crv} &= 1 - \frac{1}{\mathcal{R}_0} \\
 P_{crv} &< P_{cr} < P_{cri}
 \end{aligned} \tag{1}$$

The final proportion of immunized population P_{cr} depends on the speed of vaccination, which falls between P_{cri} and P_{crv} for disease with \mathcal{R}_0 that is bigger than 1.

Covid-19, specifically, with the \mathcal{R}_0 to be 2.79, the P_{cr} should be within the range of 64.16% to 87.15% (Equation (1)).

Herd immunity in a dynamic environment

Vaccination with different intervention scenarios



The actual scenario is way more complex than model: the efficacy of the antibody/vaccine is generally lower than 100%, its effectiveness also wanes as the time passes.^{17,18} By assuming an exponentially decay of immunity, we explored the effect of different interventions with relatively low speed of vaccination (0.1% of the population per day).

With 1000 active cases at reopening, all the intervention strategies did contribute to the reduction of the cases. However, neither of these can solely brought the \mathcal{R}_t to a level which lower than 1 - with social distancing and quarantining severe cases, the \mathcal{R}_t of the virus in the second wave is brought down to 1.619

(1.685 – 1.591 95% CI) and 2.331 (2.391-2.228 95% CI) respectively - a third wave can be observed. The combined strategy brought down the \mathcal{R}_t to 1.251 (1.331-1.143 95% CI), which did not stop the second wave, but it did prevent the third wave with a \mathcal{R}_t of 0.978 by April in 2021. If the reopen take place in August (assuming the vaccine can already be developed at this time) with approximately 1,000 active cases, the pandemic is expected to elongated to April, 2021 or even later.

With quarantining and social distancing both in practice, the critical proportion to stop the transmission of the virus is approximately 36%, which is significantly lower than the one without intervention (64.16% to 87.15%). If the vaccination speed is 0.1% of the population per day (for Canada, which is approximately 38,000 people vaccinated per day), it may require up to 400 days to reach this level due to the waning immunity. Overall, multiple strategies (i.e. school closure, social distancing, and quarantining cases) are still required even with the presence of the vaccine.

Vaccination with different speed

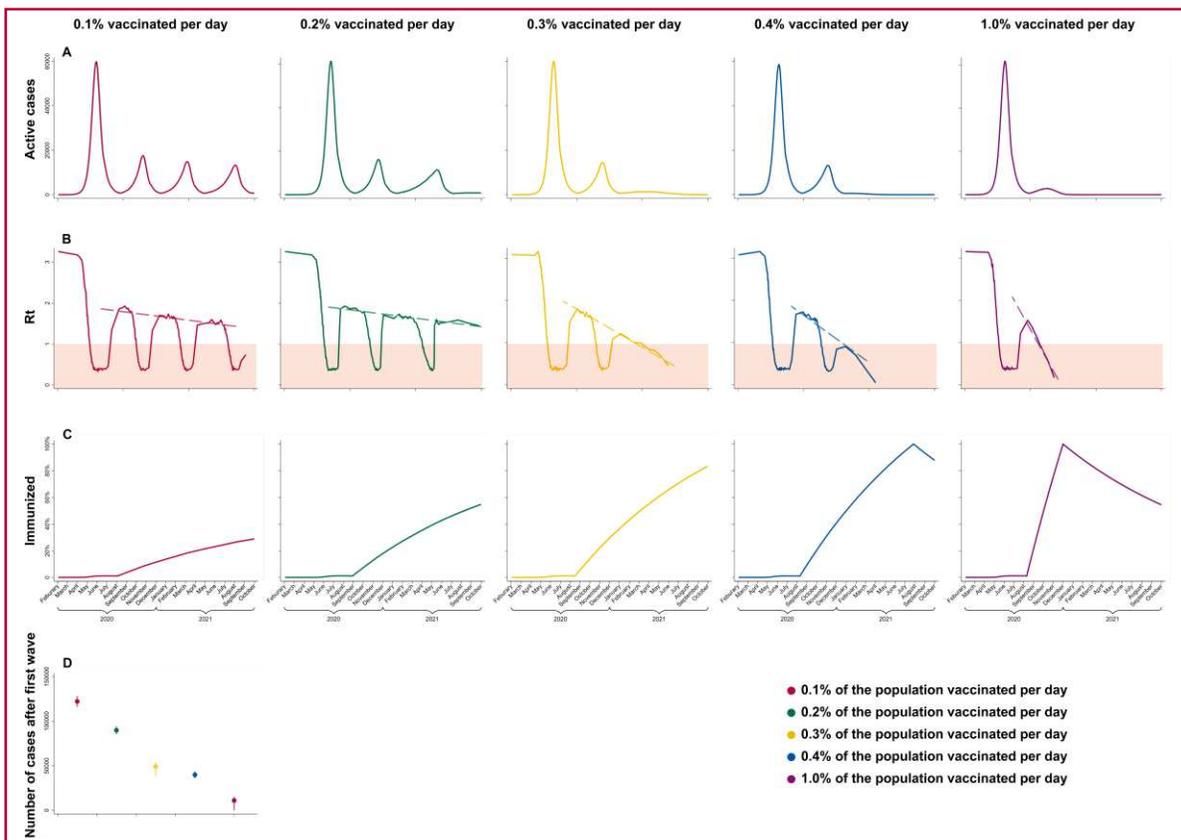


Figure 3 Effect of speed of vaccination on the economy reopening

(A) Number of active cases with different vaccination speed with social distancing, the lockdown is triggered when number of active cases is over 10,000, city reopen triggered when the number of active cases is below 1,000 (the shadow area represent the first wave before reopen, the dotted line is the effect of the vaccination on \mathcal{R}_0); the vaccination would start when the reopen starts. (B) Calculated \mathcal{R}_t during virus transmission, the \mathcal{R}_t data were not shown when the virus is eliminated. (C) The immunity within the population (percentage), the vaccination would stop when all of the population is vaccinated, the efficacy of the vaccine/antibody was assumed to wane exponentially. (D) Number of cases after the first wave with 0.1%, 0.2%, 0.3, 0.4, and 1.0% of the population vaccinated per day.

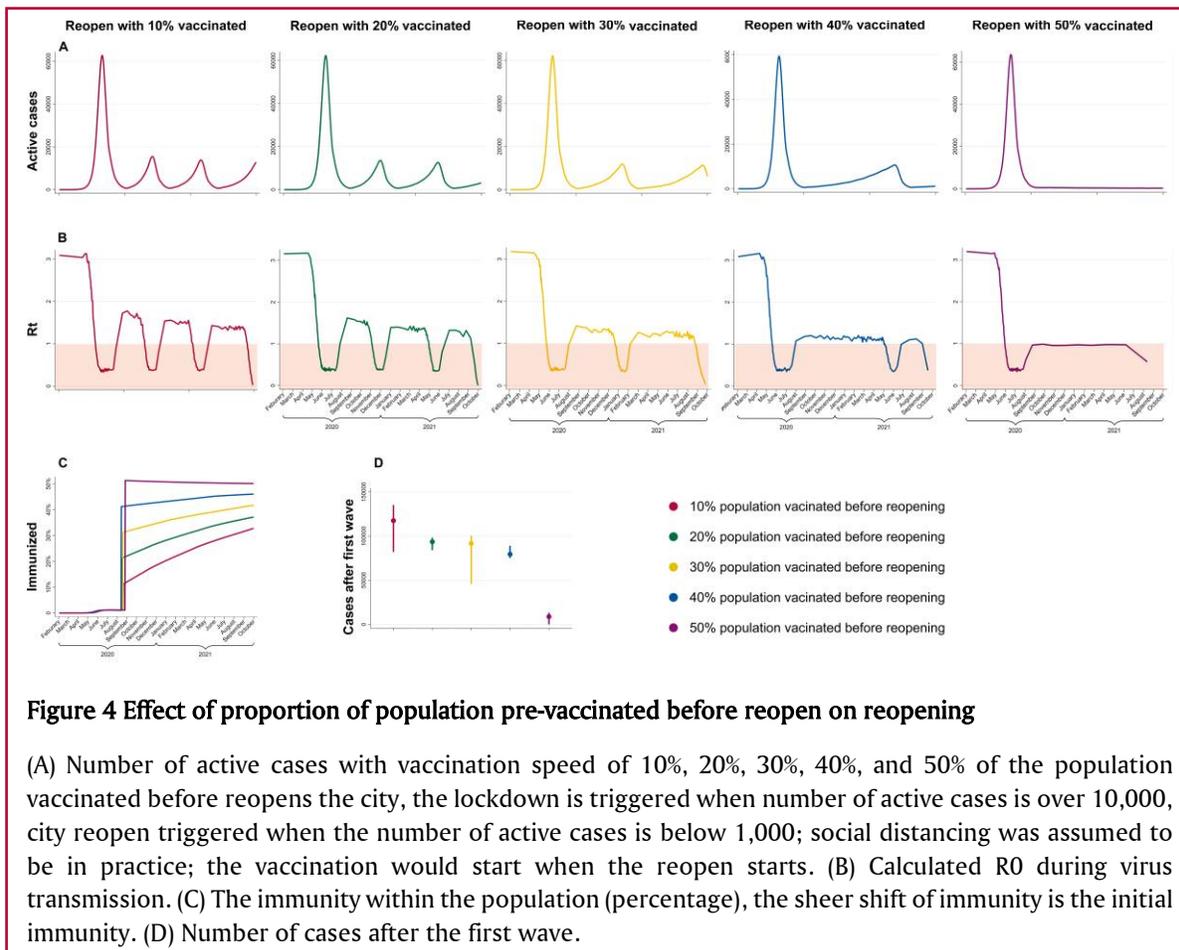
A linear relationship between the vaccination speed and \mathcal{R}_t was observed, thus lead to an negative relationship between vaccination speed of number of cases after the first wave (Figure 3B,D).

A fourth wave can be expected out of the observation range (\mathcal{R}_t should be higher than 1) with the vaccination speed of 0.1% (122261 cases after the first wave until October, 2021), and 0.2% (89903 cases after the first wave until October, 2021) per day. A vaccination speed lower than 0.2% of the population per day would lead to a convergence of population immunity that lower than 1, meaning that the 100% immunity is unreachable.

The speed of vaccination demonstrated a huge impact on the number of cases after the first wave. With 0.3% of the population vaccinated per day, the virus can be eradicated within the observation range, its third wave is also alleviated substantially. A vaccination speed higher than 0.4% of the population per day could eliminate the third wave, since the normal life can be restored as early as February, 2021.

With a vaccination speed of 1.0% of the population per day, the second wave is barely noticeable, which dwindled the final number of cases after the first wave to 10983.

Pre-vaccination before reopening



The vaccination before the reopening did result in the reduction of the severity of the epidemic at peaks for the upcoming waves, the pressure on the medical system is lowered. However, unexpectedly, the contribution of higher proportion of population pre-vaccinated before reopen is relatively limited lowering number of cases (vaccinated proportion of 20%, 30%, and 40% of the population contributed to the reduction of 20.4%, 22.0%, and 32.4% compare to 10% vaccinated) after the first wave when the proportion

is below 50% (Figure 4). There is no denying that the vaccine can contribute to the containment of the virus to a huge extent, but the impact is not significant when the vaccinated population is below a certain level (an immunized proportion of 49.6%).

Discussion

Herd immunity plays a crucial role preventing the outbreak of some seasonal flu and infectious diseases, creating a shield for vulnerables. Our study demonstrated that, in a dynamic environment which individuals' immunity gained through multiple ways, the final proportion of infected population can be up to $1 - \frac{1}{\mathcal{R}_0^2}$; with the \mathcal{R}_0 of Covid-19 to be 2.79, the number can be up to 87.15%, which is substantially higher than the minimum proportion required to reach previously predicted.¹⁶ We believe that the herd immunity strategy will not contribute to any reduction of the number of cases, the final number of proportion infected could be significantly higher than 64.16% (Figure 1 B).

Our simulation shows that some strict intervention strategies (i.e. quarantining patients, self isolation, social distancing) are still necessary to mitigate and flatten the curve. Even with vaccine and combined control measure (social distancing, quarantining severe cases, and self-isolation), the epidemic still could last no shorter than 400 days (Figure 2 A). The vaccine cannot prevent the second wave, but it can help mitigate the strength of the third wave. The number of cases can be reduced up to 76.19% with combine intervention compare to control group without any intervention (Figure 2 D). The social distancing and mask-wearing have to be normalized to control the spreading of the virus. Nevertheless, some economic activities could be reintroduced with social distancing.

The speed of vaccination would demonstrate a significant and direct impact on the mitigation, a vaccination speed of over 0.3% of the population per day is favored (with a vaccination speed less than 0.2% of the population per day, the equilibrium of waning immunity would be reached below 1). A jump in the strength of third wave was observed when the vaccination speed is above a certain level (Figure 3 A), a vaccination speed above 0.4% of the population per day can bring the \mathcal{R}_t down to a safe level to stop the spreading of the virus. Nevertheless, a direct and steep reduction of the severity from vaccine of the epidemic should not be expected since the speed of production is limited.

Although it is misleading that to conclude that the proportion of population immunized before reopening does little contribution to the mitigation, it did result in some insignificant shift of the number of cases when it is lower than 49.6% (Figure 4 D). It could take as long as 500 days for the such a vaccination level to be reached in a large country like Canada. Immunizing the population lower than this threshold before reopening did insignificant help to the containment of the virus. Thus, our conclusion is that the vaccination and reopen should proceed in parallel.

However, the production of the vaccine may not be able to match the requirement to prevent the second and third wave. Some level of social distancing and intervention measures are still needed in the foreseeable future. The real-world-scenario is more complex, some unpredictable events may lead to disastrous surge in the number of cases, which means that we may need as long as 2 years until we can restore to normal life.

We made some assumptions that may limit the precision of our conclusion - assuming an even distribution of the population, as well as the exponential decaying pattern of the waning immunity – which could cause our projection to be lower than the actual scenario since the virus tend to spread more rapidly in population-condensed areas.¹⁹ The abnormal surge and plunge of the spreading speed was not taking into consider, so the projection could be more flat but also may be deviated from the actual case.

In Canada, shopping centers and restaurants are reopening orderly, but the risks should not be underestimated as well. Despite the fact that the curve of daily new cases has been stabilized, it does not mean that it is ready for the complete reopen. With limited supply of vaccine, non-medical interventions

could be more important. Overall, we should not overestimate the effect of vaccine to help reducing the pressure on the medical system, multiple restrictions still have to be enforced.

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Author statements

We declare no conflicts of interest.

Figures

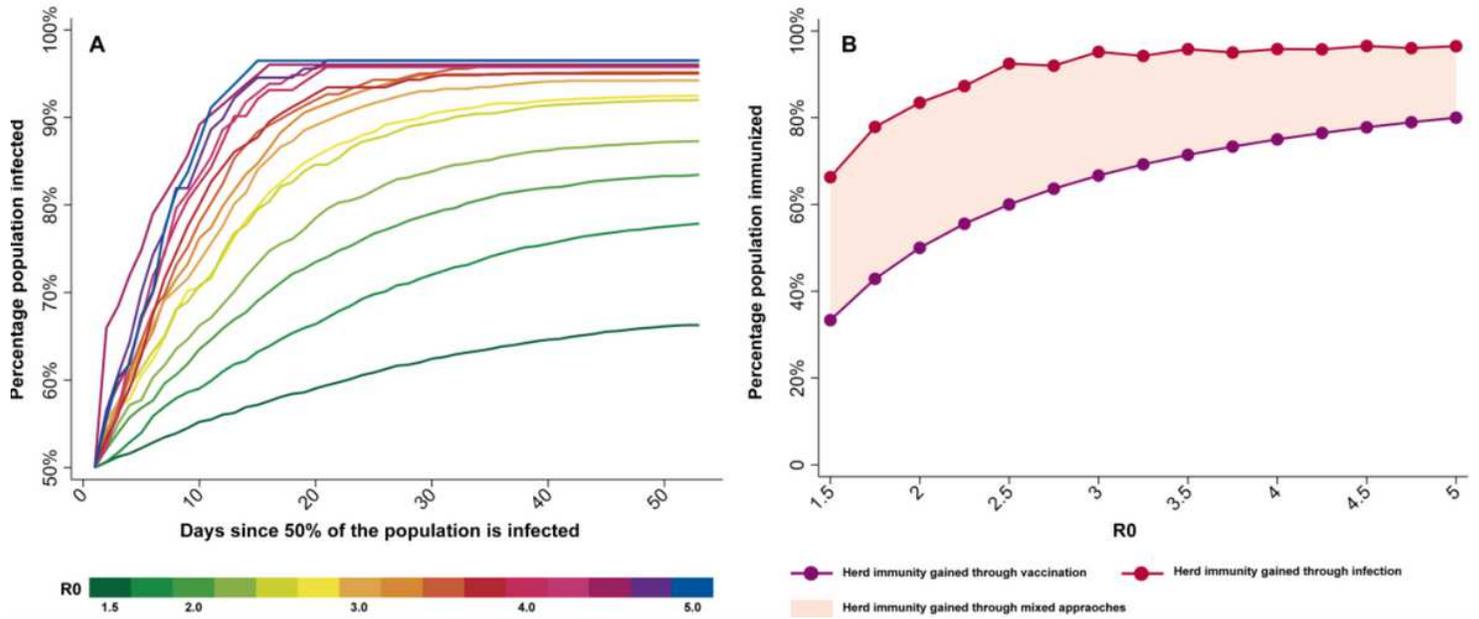


Figure 1

Effect of R_0 on the critical proportion of herd immunity of Covid-19 (A) Percentage population infected by the virus when the R_0 changes, the R_0 increases as the color become closer to violet, the simulations were based on a target population distributed evenly with a total population of 1,000,000, the lines were the most representative ones from 10 simulations. (B) A comparison of percentage population infected through vaccination and infection; the percentage population infected with immunity gained through mixed approaches is expected to be in the light pink area.

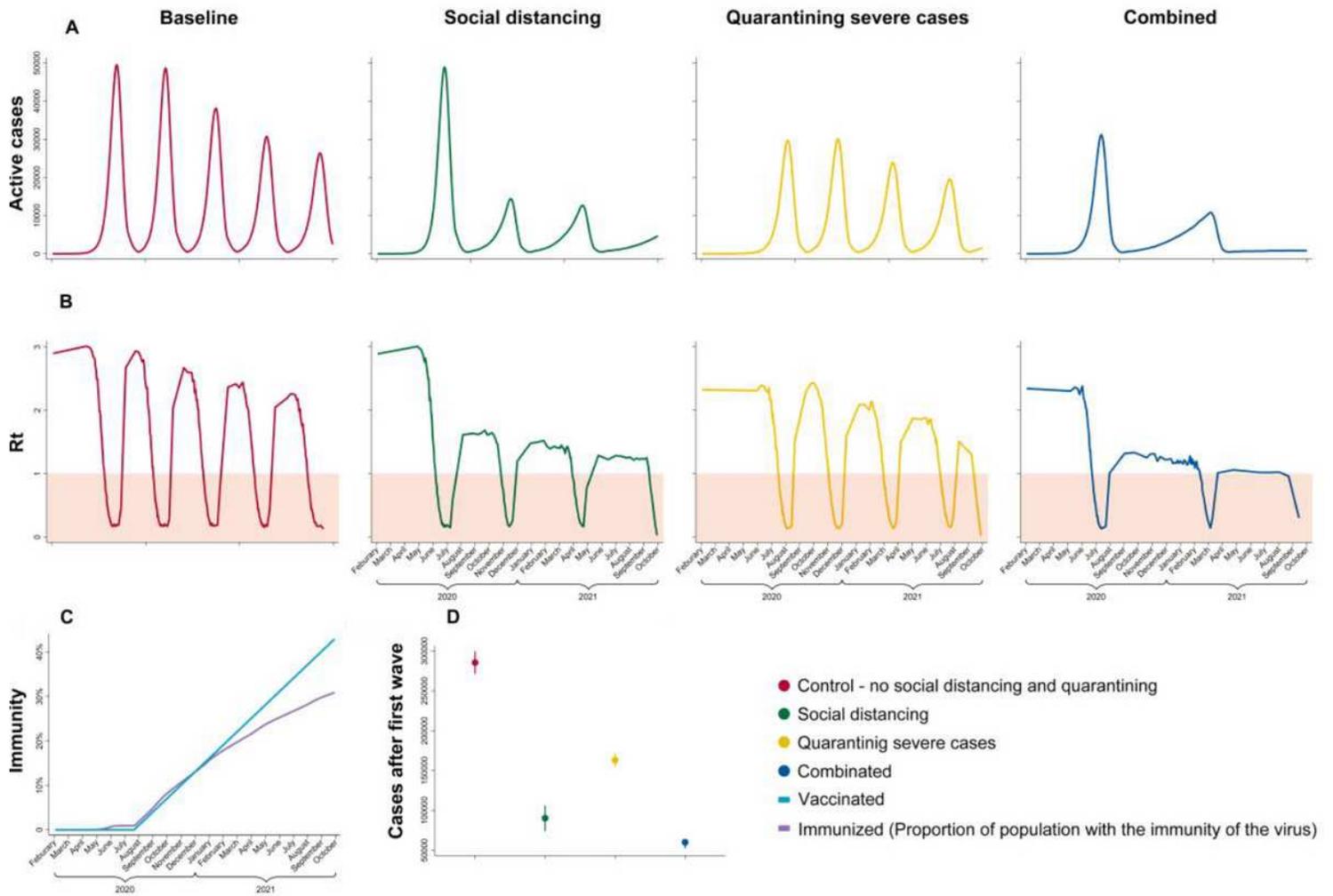


Figure 2

Effect of strategies taken on the number of cases with vaccination (A) Number of active cases with certain vaccination speed with: baseline scenario, social distancing, quarantining severe cases (19.1% of symptomatic cases), and combined strategies; the lockdown is triggered when number of active cases is over 10,000, city reopen triggered when the number of active cases is below 1,000; the vaccination would start when the reopen starts. (B) R_t during virus transmission, the R_t was calculated by finding the average number of people infected from every patient from each 1,000 patients. (C) The immunity within the population (percentage), the purple curve is the proportion of population who is immunized with high efficacy of the antibody, the blue curve is the proportion of population who were vaccinated (does not necessarily immunized from the virus due to the waning immunity). (D) Number of cases after the first wave.

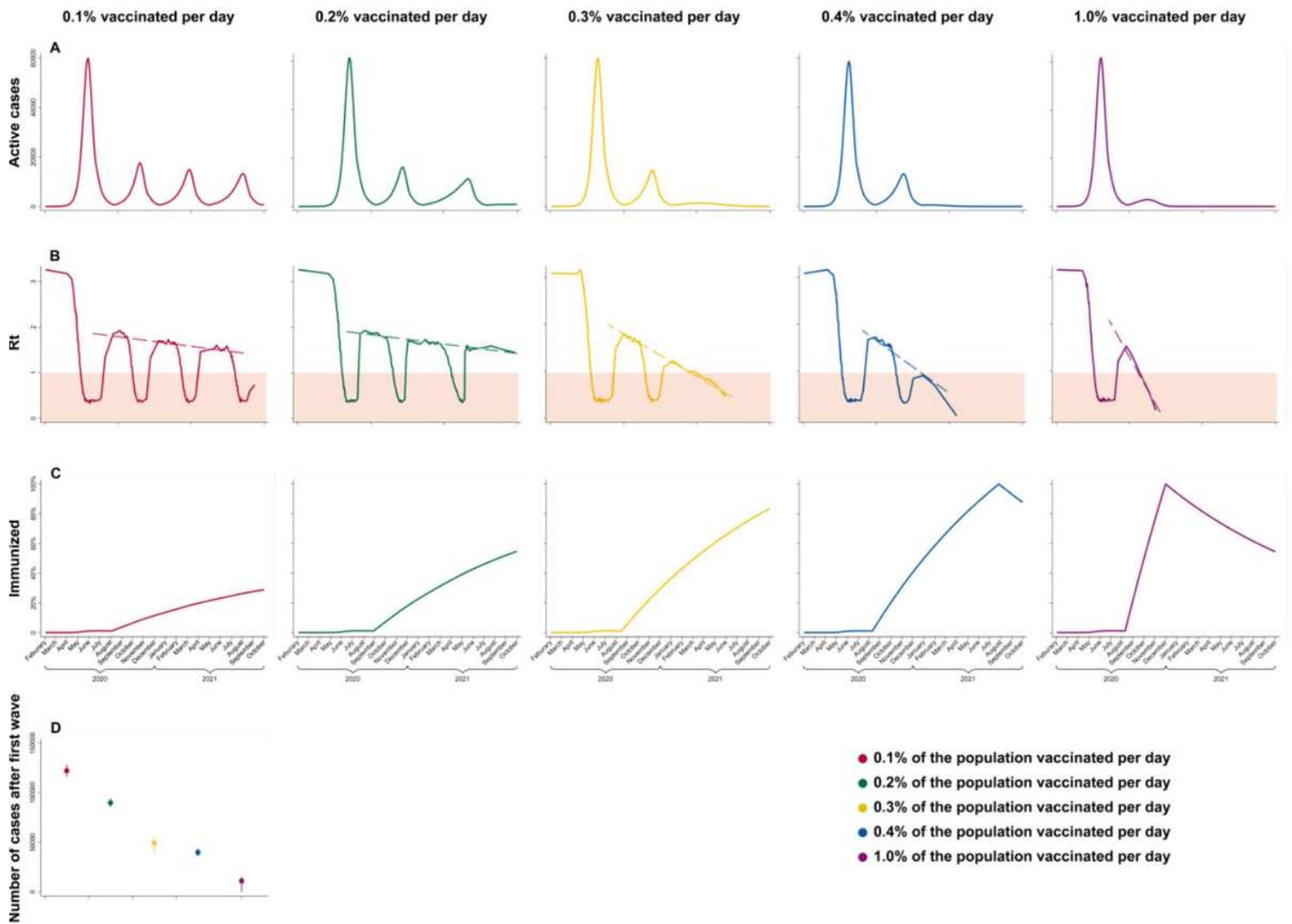


Figure 3

Effect of speed of vaccination on the economy reopening (A) Number of active cases with different vaccination speed with social distancing, the lockdown is triggered when number of active cases is over 10,000, city reopen triggered when the number of active cases is below 1,000 (the shadow area represent the first wave before reopen, the dotted line is the effect of the vaccination on R_0); the vaccination would start when the reopen starts. (B) Calculated R_t during virus transmission, the R_t data were not shown when the virus is eliminated. (C) The immunity within the population (percentage), the vaccination would stop when all of the population is vaccinated, the efficacy of the vaccine/antibody was assumed to wane exponentially. (D) Number of cases after the first wave with 0.1%, 0.2%, 0.3, 0.4, and 1.0% of the population vaccinated per day.

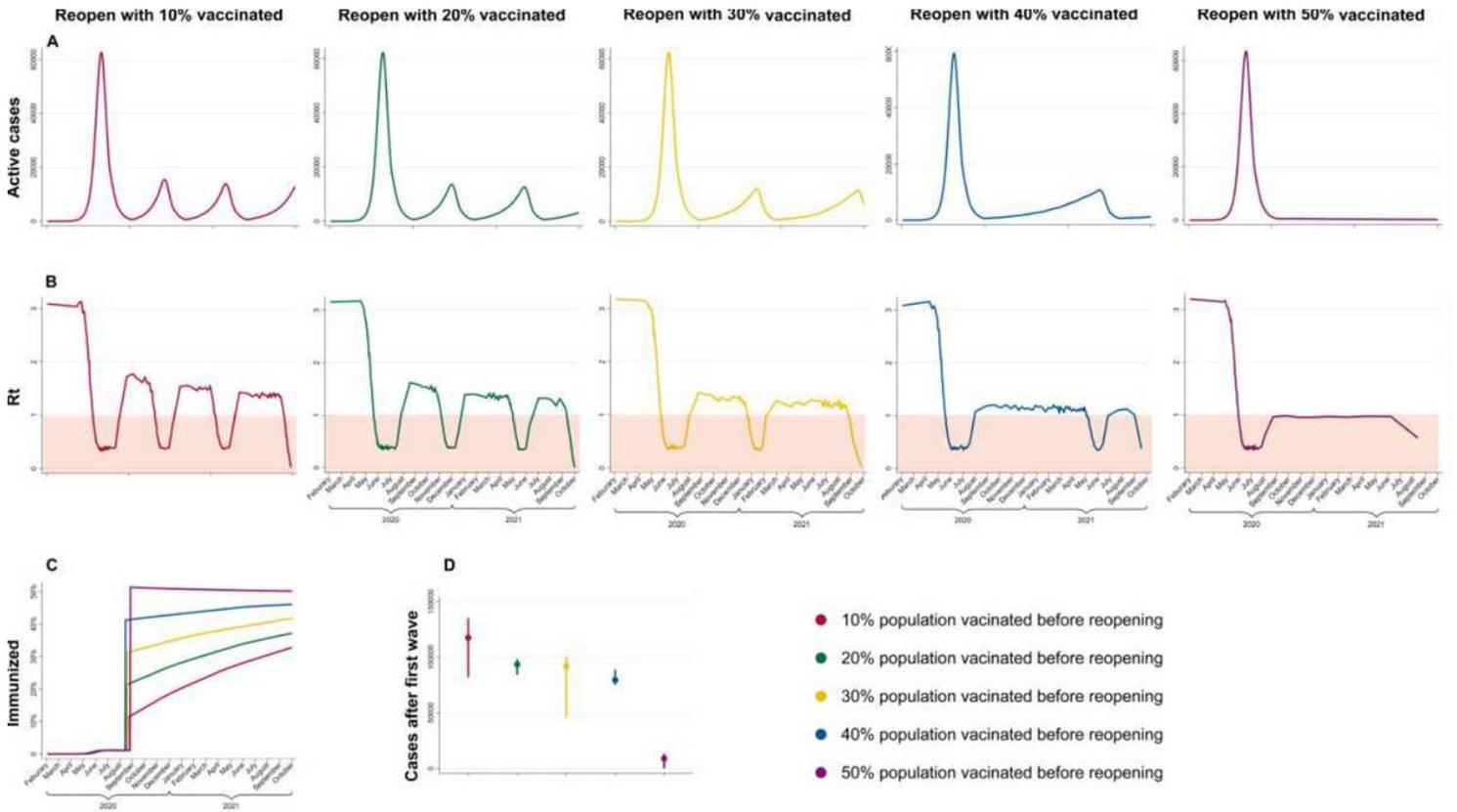


Figure 4

Effect of proportion of population pre-vaccinated before reopen on reopening (A) Number of active cases with vaccination speed of 10%, 20%, 30%, 40%, and 50% of the population vaccinated before reopens the city, the lockdown is triggered when number of active cases is over 10,000, city reopen triggered when the number of active cases is below 1,000; social distancing was assumed to be in practice; the vaccination would start when the reopen starts. (B) Calculated R_0 during virus transmission. (C) The immunity within the population (percentage), the sheer shift of immunity is the initial immunity. (D) Number of cases after the first wave.