Getting jab or regular test: a comparison and uncertainty analysis

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In preparation

Abstract

Several safe and effective vaccines are available to prevent people from getting seriously ill or dying from the coronavirus disease 2019 (COVID-19) and widespread vaccination is believed to be a critical tool to fight the disease. Universal vaccination programs are highly recommended in many countries and regions. However, individuals with vaccine hesitancy or other medical conditions may choose not to vaccinate, and regular compulsory testing is required in some sectors for such unvaccinated individuals. It is interestingly to find that different sectors pose various testing frequencies, for example on a weekly or biweekly basis, and it becomes an important scientific problem to determine the test frequency and identify underlying factors. This study formulates a population based model to accommodate different personal decision choices (getting vaccination or regular tests), vaccine efficacies and uncertainties in the epidemic transmission. By employing some typical indices to characterize the epidemic transmission, such as the basic reproduction number, the peaking time, final size, number of hospitalizations, the regular test frequency can be determined for a given set of parameters involving transmission process, vaccine efficacy and testing efficiency. The frequency of regular test is shown to be sensitive to various factors in the transmission process and vaccine efficacy, in particular, the epidemiological quantities of great concern.

Key words and phrases: Epidemiological model; vaccine efficacy; test frequency; COVID-19

1 Introduction

Since the novel coronavirus (SARS-CoV-2) outbreak (COVID-19) was asserted by the World Health Organization (WHO) as a global pandemic in March 11, 2020, most countries have implemented mandatory non-pharmaceutical interventions (NPIs) including social distancing and lock-down strategies to control the transmission [1, 2]. This unforeseen pandemic brought global economic and social activities to a standstill. SARS-CoV-2 vaccines are expected to be the life-saving straw to release the restrictions caused by COVID-19 and get back to normal life. However, on-going COVID-19 mass vaccination failed to establish herd immunity due to imperfect vaccine efficacy and relatively low vaccine coverage. In parallel with vaccination, COVID-19 testing can serve as an aided preventive measure during and post vaccination era. Existing COVID-19 tests mainly contain two types: viral test and antibody (serology) test, which can detect current and past infection respectively [4]. Nucleic acid amplification tests (NAAT) and antigen tests are now available viral tests, some of which can produce results in 15-30 minutes [11]. Polymerase chain reaction-based (PCR) tests as a type of NAAT are widely used in most countries. Besides, some types of NAAT and antigen tests can be produced into portable COVID testing kits, which offered a new option for self-testing at home. Before the implementation of mass vaccination, these convenient rapid tests

for SARS-CoV-2 have exhibited indispensable roles in identifying infected population especially the asymptomatic and pre-symptomatic individuals [5, 6, 7]. Recently, to boost COVID-19 vaccination rate and timely mitigate the spread of constantly emerging new cases, a growing number of local governments have called for compulsory vaccination reporting or regular testing for unvaccinated frontline workers or other public event participants.

The Hong Kong Government recommended all government employees should get vaccine jab starting from August 2, 2021 [36]. In lieu of getting fully vaccinated, individuals with contraindications for a type of COVID-19 vaccine or medical conditions set on guidance posed by the Hong Kong Centre for Health Protection Hong Kong SAR Government [37] may have regular tests. Those opting out of receiving vaccination are required to undergo PCR tests using combined nasal and throat swabs at community testing centers every two weeks [36]. All members in some sectors and companies are posed with similar arrangements. In order to resume normal teaching/learning and other campus activities from Semester 1 of 2021/22 academic year, most major universities in Hong Kong set similar arrangements, with surprisingly different testing frequency, either on a weekly or biweekly basis: weekly testing for students in The Hong Kong Polytechnic University for face-to-face classes [41] and dormitory residents in The University of Hong Kong [43], while biweekly testing for members in The Hong Kong University of Science and Technology [42], all members in The Chinese University of Hong Kong [45] and Hong Kong Baptist University [46] as well as student-residents in The Education University of Hong Kong [47].

Similar compulsory policies on vaccination/regular testing has been made by other local governments. The Singapore government has initiated mandatory Vaccinate or Regular Testing (VoRT) Regime from 1 October 2021, which stipulates medically eligible employees either to be vaccinated against COVID-19 or to undergo regular testing [24]. The selected sectors covering health-care, education, social and food services are subjected to the VoRT regime. The testing frequency is twice a week for unvaccinated employees in selected sectors [24]. The White House have issued an announcement in late October, which required all US federal workers and contractors should either receive coronavirus shots or get regular testing [15]. Before this announcement, some local governments including New York City, the state of California, Los Angeles and other localities have enacted similar policies on city employees [16]. The Occupational Safety and Health Administration (OSHA) have rolled out an emergency temporary standard for enterprises with 100+ employees [17]. Based on this standard, these employers must formulate mandatory vaccination policies to require employees fully vaccinated by Jan. 4, 2022, and unvaccinated employees must get COVID-19 testing at least once per week . Many universities in US including Stanford University [21], UC Davis [18], Clark University [19] and University of Stirling [20] have complied with these requirements.

During recently passed November, the Canada government has rolled out a framework on mandatory COVID-19 vaccination or testing requirements for employees in the core public administration [10]. Before the establishment of this framework, major universities in British Columbia including Simon Fraser University, the University of British Columbia, Thompson Rivers University and the University of Victoria already required their staff/students who did not disclose vaccination status to get regular tests [22]. Although there is no specific official compulsory policies on vaccination/regular testing for non-healthcare workers, the National Health Service (NHS) encouraged everyone (especially unvaccinated) in UK who do not display symptoms of COVID-19 to take regular free rapid COVID-19 testing twice weekly from 9 April, 2021 [12]. Some well-known universities in UK, such as University of Oxford [13] and University of Kent [14] have provided regular symptom-free testing per week and twice a week respectively for staff and students using or providing college or University on-site services. Other areas with official policies on COVID-19 vaccination/regular testing requirements can refer to Table 1.

Table 1: Regional policies on vaccination or regular testing for COVID-19

Regions	Policy on Vaccination/Regular testing	Fully Vaccination Coverage	Testing Frequency
Hong Kong, China	Mandatory for government employees and members in some sectors and companies [36]	67.3 % [9]	per week/ biweek
Singapore	Mandatory for frontline workers in selected sectors covering health-care, education, social and food services [24]	83.4 % [9]	per week/ twice a week
Britain	Mandatory for NHS workers and other care-home workers [12]	69.6 % [9]	twice a week
United States	Mandatory for all federal workers and contractors [15]	59.5 % [9]	per week/ twice a week
Canada	Mandatory for employees in core public administration [10]	78.2 % [9]	regularly, no specific frequency
Egypt	Mandatory for public sector workers [8]	13.7 % [9]	per week
Kazakhstan	Mandatory for people working in groups of 20+ [8]	44.1 % [9]	per week
Philippines	Mandatory for in-office workers and employees in public transportation services [8]	41.1 % [9]	regularly, no specific frequency

After a comprehensive review of regional policies on vaccination/regular COVID-19 test, the difference in testing frequency poses interesting questions worthy of further exploration: how to judiciously choose the testing frequency and which are the most influential factors determining this choice. Intuitively, the uncertainty in the transmission process, the efficacy of vaccination program and the testing efficiency play joint roles in determining the testing frequency. To obtain more accurate answer, a population based model will be formulated in this manuscript. Indeed, a small amount of model-based studies on COVID-19 testing focused on investigating the combined effects of regular screening/testing strategy with other NPI strategies in the pre-vaccination era. Grassly et al proposed a mathematical model to compare different testing and isolation strategies and found that weekly screening/PCR testing of health-care workers and other groups with high-risk would effectively reduce the effective reproduction number [25]. Wells et al attempted to explore the optimal testing time during quarantine that would reduce the probability of post-quarantine transmission [26]. As mass-vaccination campaign was conducted, a very recent preprint proposed a stochastic compartmental model to evaluate the joint effects of vaccination and asymptomatic testing uptake on containing the spread of SARS-CoV-2 in a university setting [27]. Compared to previous modelling studies on testing, our model-based study will focus on exploring the equivalent preventing effects of regular COVID-19 testing as getting vaccination. Various model parameters in terms of the virus transmission, vaccine efficacy and testing efficiency reported from existing studies will be fed to project the suitable test frequency. Further sensitivity analysis will be conducted to illustrate the impact of various factors on determining the test frequency.

2 Methodology

We will empty a model-based approach to the problem by first formulating an epidemiological model, and perform the uncertainty and sensitivity analysis about the impact of test frequency on some epidemiological quantities, such as the basic reproduction number, the peak size of infections, the number of hospitalizations and deaths.

2.1 The epidemiological model

We are going to formulate a compartmental model, by dividing the individuals into different classes or groups and describes how individuals in different "compartments" in a population interact, based on feature of the question in the investigation. In the current problem, individuals in the whole population may experience distinct stages of disease transmission, vaccination states (vaccinated or unvaccinated), and different testing dates for those unvaccinated ones.

2.1.1 All-or-nothing vaccines

After getting the COVID-19 vaccine, the host may not immediately get protection since it is recognized that the immune system needs 2-3 weeks to build immunity [52, 53]. Moreover, the "all-or-nothing" vaccination mechanism is assumed in this modelling framework. Therefore, the vaccinated population in the study sector can be stratified into: vaccinated group V who have yet acquired immunity, vaccinated group V^f with failure efficacy (including individuals who receive no protection from the vaccine), and vaccinated group with full protection will be excluded from the transmission processes and moved to the removed class. SARS-CoV-2 infected people may develop symptoms while some may remain asymptomatic. However, the exact proportions of asymptomatic and symptomatic infections remain unknown, which may vary with age due to the increasing prevalence of underlying conditions in older age groups [39, 34]). Therefore, we did not distinguish the asymptomatic and symptomatic infections and extend the well-accepted susceptible-infectious-removed compartmental structure to account for age-specific transmission characteristics. Here, we consider only susceptible individuals as the target population for vaccination. For each age group i, unvaccinated susceptible population (S_i) will be vaccinated at least one dose of the two-dose vaccine, and the vaccinating rate is determined by the vaccine allocating rate. The vaccinated population involved in the disease transmission process contains both newly vaccinated individuals (V_i) and individuals who have acquired failed protection (V_i^f). The infectious class I_i includes both asymptomatic and symptomatic individuals in the infectious stage. The removed class R_i contains individuals who can no longer infect others. Similar compartmental structures are used in the existing study to explore the optimal COVID-19 vaccination strategy [30]. The disease transition diagram is shown in Figure 1. The rates of change for these classes are described by the following set of differential equations.

$$
\begin{cases}
\frac{dS_i(t)}{\partial t} = -v_i(t) - \lambda(t)S_i(t), & \text{susceptible, unvaccinated,} \\
\frac{dV_i(t)}{\partial t} = v_i(t) - dV_i(t) - \lambda(t)V_i(t), & \text{newly vaccinated who have yet acquired immunity,} \\
\frac{dV_i^f(t)}{\partial t} = (1-e_i)dV_i(t) - \lambda(t)V_i^f(t), & \text{vaccinated with failed protection,} \\
\frac{dI_i(t)}{\partial t} = (S_i(t) + V_i(t) + V_i^f(t))\lambda(t) - \gamma I_i(t), & \text{infected,} \\
\frac{dR_i(t)}{\partial t} = \gamma I_i(t) + e_i dV_i(t), & \text{removed, vaccinated with full protection,}
\end{cases} \tag{1}
$$

where $v_i(t)$ represents the vaccine allocating rate for age group i, $1/d$ denotes the time delay between getting the first jab and obtaining immunity against the disease, e_i is the proportion of population who have acquired full immunity in the all-or-noting vaccination scheme, γ is the removed rate for infected individuals. The force of infection is expressed as

$$\lambda(t) = \beta \sum_{j=1}^{J} s_i C_{i,j} \frac{I_j(t)}{N_j},$$

and $C_{i,j}$ in the above equation describes the contact matrix and s_i quantifies the difference of susceptibility to infection among distinct age groups.

The remaining unvaccinated individuals will receive regular test with fixed frequency, i.e., one testing round from day 1 to day T. Assume that testing results of unvaccinated individuals are reported at the same time instant $nT + m$, then some, but possibly not all, individuals with high virus loads will be screened out and isolated. Here, n represents the $n - th$ round of the T-period. Suppose ρ measures the testing efficiency, that is the proportion of positive cases identified out of all tested individuals, then a proportion of ρ of unvaccinated susceptible (S_i) individuals getting regular test will be isolated from the community to the removed class R_i. There are abrupt changes in these variables on $t = nT + m$, as sketched in the diagram (Figure 1(b)) which can be described by impulsive terms mathematically as follows

$$\begin{aligned} S_i((nT+m)^+) &= (1-\rho)p_m S_i((nT+m)^-), \\ R_i((nT+m)^+) &= R_i((nT+m)^-) + \rho p_m S_i((nT+m)^-), \end{aligned}$$

where p_m is the proportion of individuals whose testing result comes out at the $m - th$ day among unvaccinated individuals. The other variables V_i, V_i^f and I_i, remain unchanged, that is

$$\begin{aligned} &V_i((nT+m)^+) = V_i((nT+m)^-), \quad V_i^f((nT+m)^+) = V_i^f((nT+m)^-) \\ &I_i((nT+m)^+) = I_i((nT+m)^-). \end{aligned}$$

2.1.2 Leaky vaccines

Model 1 can be replaced by the following model 2 in the case of leaky vaccines, that is the vaccine reduces the susceptibility of all vaccinated individuals to infection, and reduces their infectiousness and risk of death if infected. In this case, all the vaccinated population will experience two vaccination stages. One is the newly vaccinated stage, where vaccinated individuals have yet acquired immunity (V_i). The other is after immunization stage, where all vaccinated individuals have acquired partial protection (V_i^p). The reduced infectiousness of vaccinated individuals in V_i^p group depends on the age-specific vaccine efficacy e_i. The rates of change for these classes are described by the following set of differential equations. The disease transmission diagram is shown in Figure 2.

$$\begin{cases} \frac{dS_i(t)}{\partial t} = -v_i(t) - \lambda(t)S_i(t), & \text{susceptible, unvaccinated,} \\ \frac{dV_i(t)}{\partial t} = v_i(t) - dV_i(t) - \lambda(t)V_i(t), & \text{newly vaccinated who have yet acquired immunity,} \\ \frac{dV_i^p(t)}{\partial t} = dV_i(t) - (1-e_i)\lambda(t)V_i^p(t), & \text{vaccinated with partial protection,} \\ \frac{dI_i(t)}{\partial t} = (S_i(t) + V_i(t) + V_i^p(t))\lambda(t) - \gamma I_i(t), & \text{infected,} \\ \frac{dR_i(t)}{\partial t} = \gamma I_i(t), & \text{removed.} \end{cases} \tag{2}$$

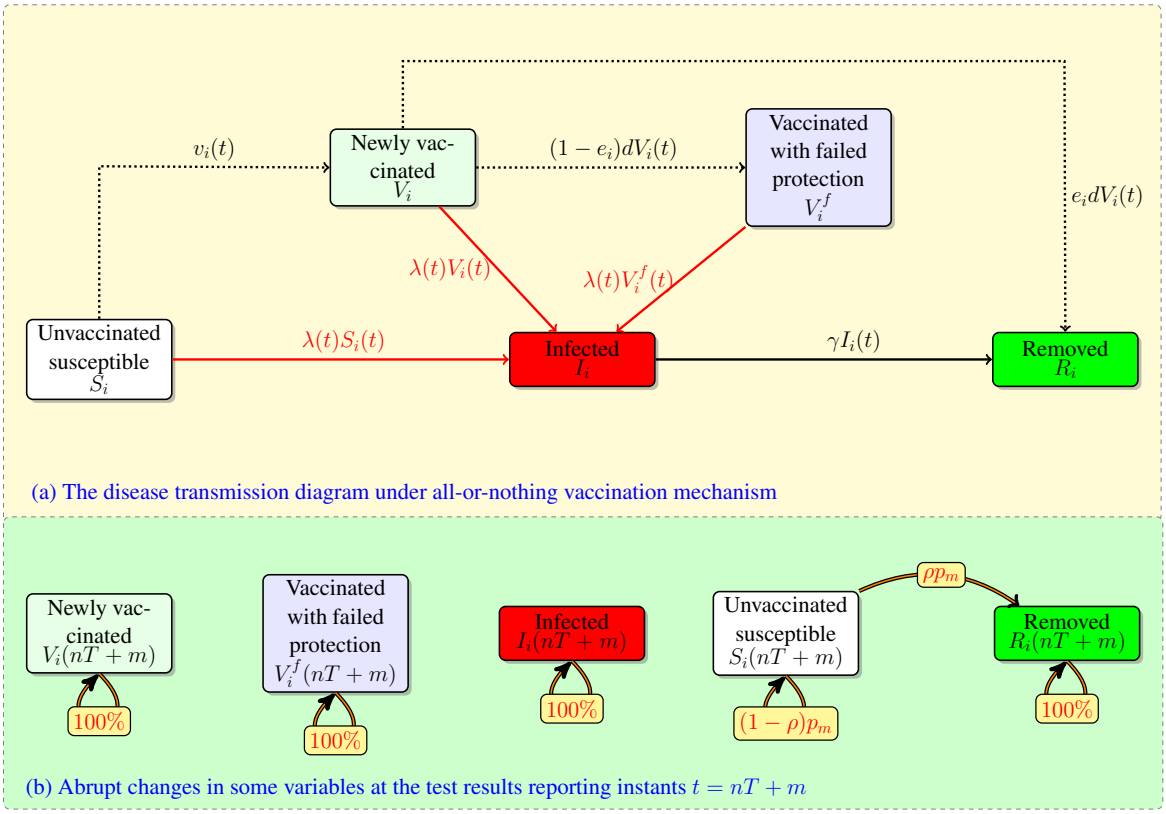

Figure 1: The diagram for the transitions rates of variables under all-or-nothing vaccination mechanism. All parameters are shown in the Table 2 and $\lambda(t)$ represents the force of infection.

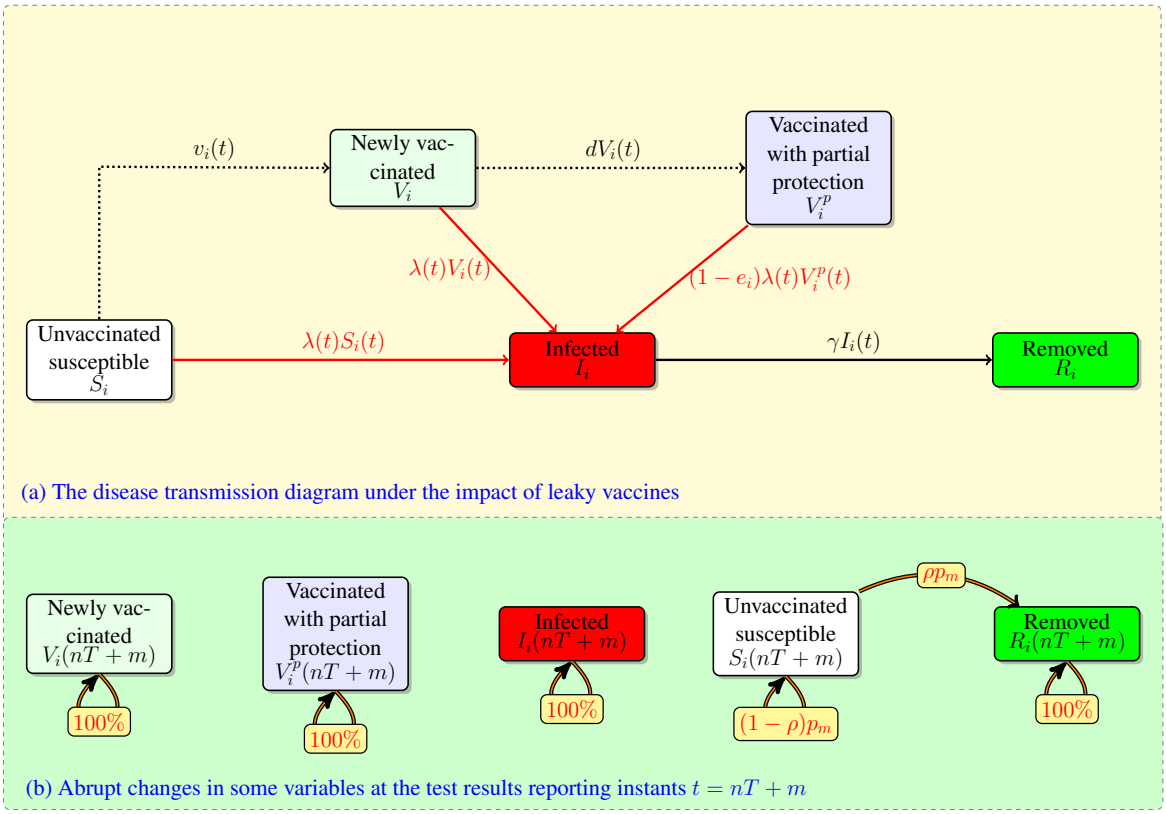

Figure 2: The diagram for the transitions rates of variables under the impact of leaky vaccines. All parameters are shown in the Table 2 and $\lambda(t)$ represents the force of infection.

The baseline parameter values, shown in Table 2, are mainly taken from existing studies, in [39, 34].

The transmission probability of symptomatic transmission is 0.053

The relative infectiousness is 0.51 0.51 and 1 for pre-asymptomatic, asymptomatic and symptomatic transmissions, as those in [31]. The baseline effective infection probability is fitted by taking the basic reproduction number to be 2.5.

The proportion of infected people who never developed symptoms in the community remains unknown [34] and several studies estimate that the proportion ranges from 6% to 41%. It is difficult to estimate the infectiousness of asymptomatic individuals, and we use that in [39]. However, the study [49] sets the ratio of infectiousness of asymptomatic individuals to that of symptomatic individuals as to be 0.1. The infectiousness of presymptomatic cases is another puzzle which has a wider range [50], and here we set the relative infectiousness to be ???.

Possible imperfect efficacy of the vaccine is modeled by introducing "leaky" parameters to characterize the partial protection and potential effects and and "all-or-nothing" parameters to account the fraction of vaccinated individuals gain no protection. A very wide range of vaccine efficacy is assumed in [30].

Table 2: Parameters and their baseline values in the model equations.

Parameter	Description	Baseline value
$1/\gamma_E$	latency period for those unvaccinated or failure vaccinated individuals	4 days [39]
$1/\gamma_E^V$	latency period for those vaccinated individuals	
p_S	proportion of individuals that will show symptoms later for those unvaccinated or failure vaccinated individuals	6% to 41% [34]
p_S^V	proportion of individuals that will show symptoms later for those vaccinated individuals	
$1/\gamma_A$	infection period of asymptomatic cases for those unvaccinated or failure vaccinated individuals	12 days [39]
$1/\gamma_A^V$	infection period of asymptomatic cases for those vaccinated individuals	10 days [39]
$1/\gamma_P$	pre-symptomatic duration for those unvaccinated or failure vaccinated individuals	2 days [39]
$1/\gamma_P^V$	pre-symptomatic duration for those vaccinated individuals	
$1/\gamma_I$	waiting time between showing symptoms and get treatment for those unvaccinated or failure vaccinated individuals	1 day (assumed)
$1/\gamma_I^V$	waiting time between showing symptoms and get treatment for those vaccinated individuals	1 day (assumed)
β_A	effective transmission rate of asymptomatic cases	0.016-0.02 [39]
β_P	effective transmission rate of presymptomatic cases	0.96-0.12 [39]
β_I	effective transmission rate of symptomatic cases	0.08-0.1 [39]
ϕ_A, ϕ_P and ϕ_I	relative infectiousness of those asymptomatic, pre-asymptomatic, and symptomatic vaccinated individuals	$[0, 1]$
ϕ_S	relative susceptibility of supscptibe vaccinated individuals	$[0, 1]$
p_V	proportion of vaccinated individuals	
p_f	proportion of vaccinated failure (leaky) cases	
p_m	proportion of individuals whose testing result comes out at the m-th day among unvaccinated individuals	
T	regular test period	
$N(t) \equiv N(0)$	the population size	
ρ	testing efficiency, represents the proportion of positive cases identified out of all tested individuals	

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