Evaluation of CoronaVac using a modified SIR model

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Abstract—In the report, effectiveness of CoronaVac on controlling COVID-19 is evaluated in an outbreak scenario in Hong Kong using a modified SIR model. The main aim of this model is to evaluate the effectiveness of the vaccination program with minimum to no social distancing measures, where the dependent variable is estimated death under scenarios.

1 Introduction

Everyone dislike social distancing measures. Despite huge controversy on the effective rate of CoronaVac of 50.4% only, the Hong Kong government has launch its COVID-19 vaccination program. And in recently, the government announce its plan to greatly loosen its control on social distancing for those who are vaccinated by either CoronaVac or Pfizer-BionTech BNT162B2. Here, we are proposing a modified SIR model to evaluate is it feasible to control an pandemic outbreak with minimum to no social distancing measures other than vaccination in a public health perspective.

2 Experiment

2.1 Proposed Model

2.1.1 The Original SIR Model

In the original SIR model[1], there are three class, namely Susceptible (S), Infected (I), Removed (R). And the change in each time unit (In the report, we are using day as unit time) is represented as:

$$\begin{aligned} \frac{dS}{dt} &= -\frac{\beta IS}{N} \\ \frac{dI}{dt} &= \frac{\beta IS}{N} - \gamma I \\ \frac{dR}{dt} &= \gamma I \end{aligned} \tag{1}$$

Where the system is non-linear,

$$\begin{aligned} \frac{dS}{dt} + \frac{dI}{dt} + \frac{dR}{dt} &= 0 \\ S(t) + I(t) + R(t) &= constant = N \end{aligned} \tag{2}$$

The variable β and γ is inversely proportional to the average time between contact and removal. Therefore the basic reproduction number R_0, which could be interpreted as the expectation of new infections caused by each case, that is average number of contacts before a person get removed.

For example, when R_0 is 3, a infected person transmits the disease to 3 others. R_0 is given in the following formula:

$$\begin{aligned} T_c &= \frac{1}{\beta} \\ T_r &= \frac{1}{\gamma} \\ R_0 &= \frac{\beta}{\gamma} \end{aligned} \tag{3}$$

2.1.2 new model

There are few key features in our proposed model that are different to the original. First, dead (D) class is introduced with fatality rate f and removed class is now separated into recovered (R) and dead (D) class. Also, among those who are recovered, some of them would lost his immunity in certain average rate δ. Third, the contact rate β is factored by the overall vaccine effectiveness $(1 - pe)$, where v is proportion of people vaccinated per day, e is combined effectiveness weighed by the ratio of people taking CoronaVac and BNT162B2. We have this multiplier instead of removing them directly from class S because these vaccinated people are still having certain chance infected, in contrast to those recovered recently who has very high immunity rate and likely self-quarantine.

For intuition, when the effective rate and vaccination rate are both 100%, all people are immune. Even citizens do make contact with each other, but no transmission could happen, and thus effective contact rate drops to zero. The new model is given as of below:

$$
\begin{aligned}
D(t) &= fI_{cumulative}(t-1) \\
\frac{dS}{dt} &= -\frac{\beta(1-pte)I(t)S(t)}{N} + \delta R(t) \\
\frac{dI}{dt} &= \frac{\beta(1-pte)I(t)S(t)}{N} - \gamma I \\
\frac{dR}{dt} &= \gamma I(t)
\end{aligned} \tag{4}
$$

2.2 Evaluation

To evaluate the effectiveness of the vaccination program, we have the following scenario: The government starts the vaccination program using plan A (BNT162B2 + CoronaVac, in 1:1 ratio as of today) or plan B (control setup, BNT162B2 only) at the beginning of the outbreak. The death numbers is then estimated and compared.

The initial conditions are estimated from 3 major outbreaks in Hong Kong. $\beta, \gamma, I_0, R_0, N$ is calculated by the average in first 7 days of each wave(continuous days with $R_0 > 0$) where there are minimum social distancing measures to simulate spread of COVID-19 under vaccination program ONLY. Note that: p, f, e are overall rates in Hong Kong up to today (4/26/2021); δ is set aggressively due to lack of clinical reports[2]; effective rate of CoronaVac = 50.14%, BNT162B2 = 91% . We have the following:

$$
\begin{aligned}
\beta &= 0.139708 \\
\gamma &= 0.040345 \\
I_0 &= 221.619 \\
R_0 &= 2164.952 \\
N &= 7545198 \\
p &= 0.00197820202 \\
f &= 0.017870885 \\
e_A &= (0.5)(0.91) + (0.5)(0.514) = 0.712 \\
e_B &= (1.0)(0.91) = 0.91 \\
\delta &= \frac{1}{280}
\end{aligned} \tag{5}
$$

3 Results

Running 180 days in MATLAB, we obtained the following:

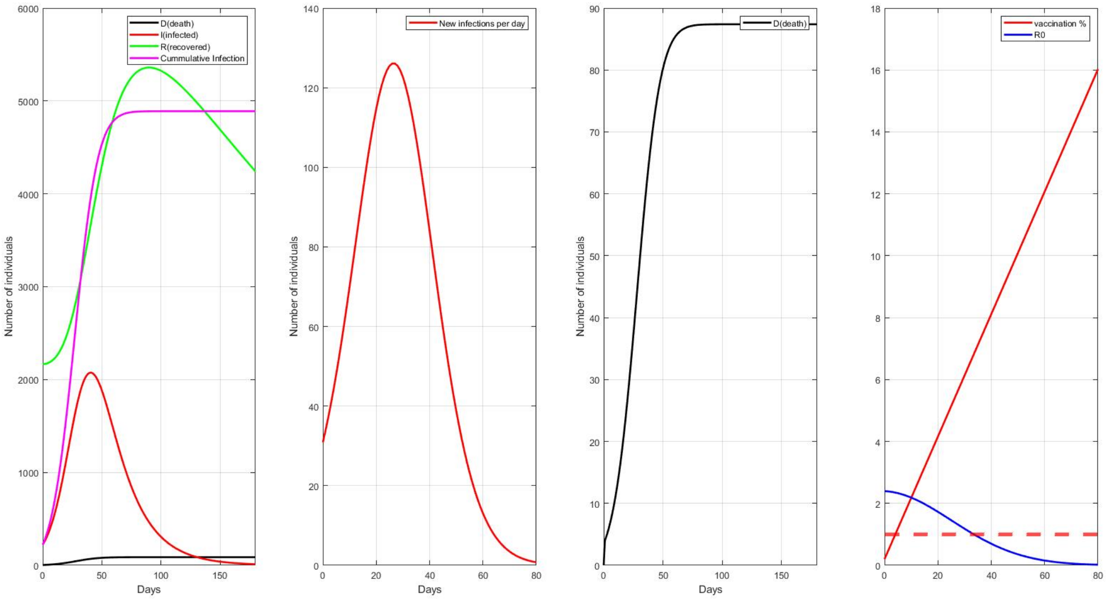

Figure 1: Plan A: CoronaVac + BNT162B2 in 1:1 ratio

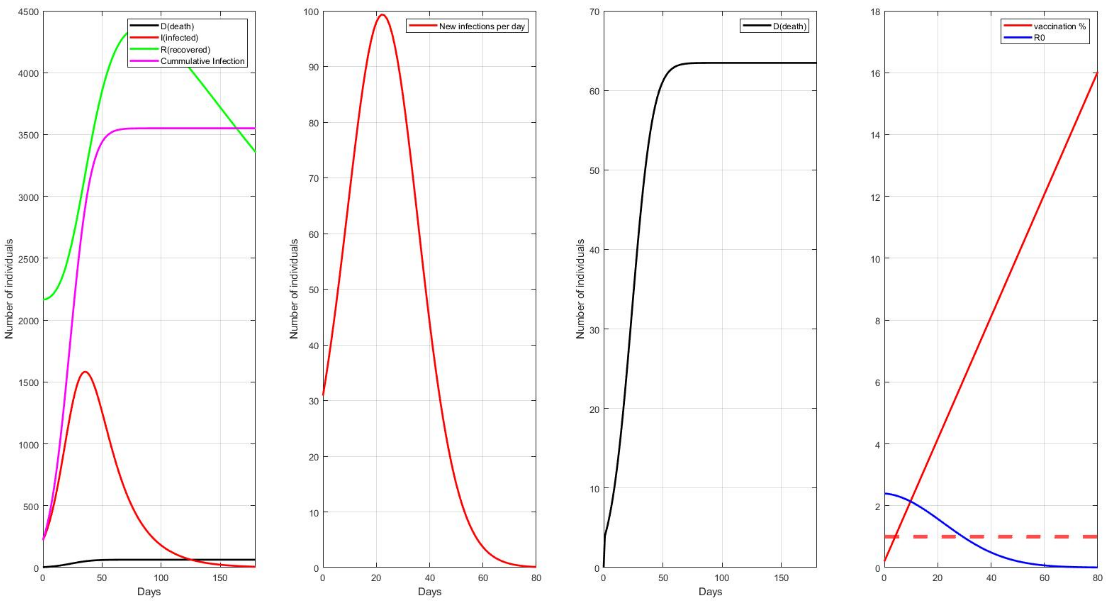

Figure 2: Plan B: BNT162B2 only

plan	A	B	percentage diff. (4 d.p.)	diff.
deaths	87.37	67.45	+29.5330%	19.92
cumulative infection	4890	3551	+37.7077%	1339
peak infected	2068	1581	+30.8033%	487
peak infection per day	126.1	99.32	+26.9634%	26.68
days for R_0 to get ≤ 1	33.5	29.5	+13.5932%	4

Table 1: Comparison of results on A and B

3.1 Discussion

The results shown is out of our expectation. In our intuition, the use of CoronaVac would have an catastrophic outcome on the death tolls by at least 2 or 3x more deaths. The death count difference is only 19.92. Such a small difference in death numbers is very small relative to Hong Kong's 7.5M population and therefore acceptable in terms of public health. This also applies to the peak infected (where we consider this parameter as number of hospitalized patients at a time) and days for R_0 getting below 1.

However, it is also worth noting that the small absolute difference benefits under small bases only. From table 1 we see that the percentage difference in death tolls and peak infected figures are about 30%. Which could be a huge threat if the outbreak scales up by tuning up β, which means no action were taken until later in the outbreak. If we pick real data on Nov 21 2020, the time when third wave confirmed cases were skyrocketing, where $\beta = 0.184449$, the outcome would become this:

plan	A	B	percentage diff. (4 d.p.)	diff.
deaths	277.4	175.2	+58.3333%	102.2
cumulative infection	15530	9801	+58.4532%	5729
peak infected	6855	4529	+51.3579%	2326
peak infection per day	435	298.7	+45.6311%	136.3
days for R_0 to get ≤ 1	38.5	34	+13.2353%	4.5

Table 2: scenario of government intervening late

By considering peak hospitalized figures, this table warns out that action must be taken as quick as possible for the vaccination program to be effective regardless of vaccine combination or the medical system would be in the risk of collapsing. Another interesting phenomenon is that, the percentage difference on days for R_0 to get ≤ 1 didn't vary much between different plans across different starting β.

3.2 Limitations of the model

We must admit that this could be an over-optimistic simulation as we have set up a lot of assumptions which makes data mining work easier. There are a lot more factors and dynamics to consider. For instance, we neglect cases coming from inbound foreigners and the initial conditions could be an underestimation since there are still some sort of social distancing throughout the year. Also, it is not feasible to back testing using real world data iterating a sufficiently long time period, as the government around the world will intervene when there is an outbreak.

4 Conclusion

The CoronaVac is actually not a bad choice in terms of public health. However, this strategy would work well only when the government intervene quickly on or before the beginning of the outbreak.

References

[1] Ng, T., Ph.D. (n.d.). The mathematics of diseases – On Modeling Hong Kong 's SARS Outbreak. . Lecture presented at SCNC1001 Science: Concepts and Notions, Department of Mathematics, HKU.

[2] Elisabeth Mahase. *Covid-19: Past infection provides 83% protection for five months but may not stop transmission, study finds*. [*BMJ 2021;372:n124*].