

How Large Fraction of a Population must be Vaccinated before a Disease is Controlled?

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Abstract

The ongoing COVID-19 pandemic has already caused more than 5 million casualties despite hard restrictions and relatively high vaccine coverage in many countries. The crucial question is therefore, how large vaccination rate and how severe restrictions are required to terminate the spread of the disease, assuming that the vaccine efficiency and the basic reproduction ratio (R_0) are known? To answer this question, a mathematical equation was applied to visualize the required vaccination level as function of vaccine efficiency, restriction efficiency and basic reproduction ratio (R_0). In addition to the modeling study, COVID-19 data from Europe was collected during 19/11-26/11 (2021) to assess the relation between vaccination rate and incidence. The analysis indicates that a vaccination rate of ~ 92% (2 doses) is required to stop Delta (B.1.617.2) without severe restrictions, under conditions like those in Europe late November 2021. A third vaccine dose, improved vaccines, higher vaccination rates and/or stronger restrictions will be required to force Omicron (B.1.1.529) to expire without infecting a large fraction of the population.

Keywords: COVID-19; SARS-CoV-2; Delta; Omicron; Vaccination; Modeling; Prediction

Introduction

The COVID-19 (SARS-CoV-2) pandemic has caused more than 5 million casualties during the years 2020-2021, despite huge global efforts to dampen the spread of the virus [1]. Several vaccines have been developed and more than 9 billion vaccine doses have already been distributed [1]. Unfortunately the virus is gradually evolving, resulting in new COVID-19 variants under monitoring (VUM), Variants of Interest (VOI) and variants of concern (VOC), including the Alpha (B.1.1.7), Beta (B.1.351), Gamma (P.1), Delta (B.1.617.2) and Omicron (B.1.1.529) variants. These variants have higher basic reproduction number (R_0) and higher resistance against today's vaccines as compared to the original COVID-19 virus.

Governments and other authorities all around the world are constantly trying to identify ideal strategies for counteracting the pandemic with minimal impact on health and economy. The aim of this study was to utilize an improved generic epidemiological equilibrium transmission model (with empirical input data) to predict required vaccination rates and restriction strengths for controlling different COVID-19 variants, including the Delta and Omicron variants. The model results can be used to optimize the preventive measures against COVID-19 variants.

Methodology

Compartmental models, like the SIR (Susceptible, Infectious or Recovered) model [2], are used in epidemiology to capture time-dependent phenomena, but the aim of this study is only to capture steady-state properties. Therefore, the mathematical model in this study was instead based on a well-known epidemiological equilibrium equation [3].

$$R_t(T) = R_0 * (1 - I(t)) * (1 - E_R(t)) \quad (1)$$

where $R_t(t)$ is the time-dependent reproduction ratio at time t , R_0 is the initial reproduction ratio without restrictions, $I(t)$ is the relative proportion of the population that is immune to the disease, and $E_R(t)$ is the relative efficiency of all preventive measures against the spread (e.g. social distancing, increased hygiene rules, face-masks, quarantines etc.). Both $I(t)$ and $E_R(t)$ are limited to the interval 0 to 1. For $I(t)$, 0 and 1 correspond to no immunity and complete immunity in the population,

respectively. For $E_R(t)$, 0 and 1 correspond to no preventive measures and complete isolation of every single individual in the population, respectively.

In this study, it was assumed that $I(t)$ equals the fraction of vaccinated persons $\phi_v(t)$ times the average vaccine efficiency $E_v(t)$, plus the fraction of recovered (non-vaccinated) persons $\phi_r(t)$ times the average preventive effect of recovering $E_r(t)$:

$$I(t) = \phi_v(t) E_v(t) + \phi_r(t) E_r(t) \quad (2)$$

Typically, $E_r(t)$ and $E_v(t)$ decreases with time, whereas $\phi_r(t)$ and $\phi_v(t)$ gradually increases. In practice, several COVID variants and vaccines with different $E_v(t)$ -values often co-exist, but for visualization and prediction purposes it is favorable to focus on one at the time. For simplicity and for pedagogical reasons, we counterfactually also assume that $E_r = E_v$ even though E_r in reality often is higher than E_v , especially after longer periods of time. This assumption gives $\phi = \phi_v + \phi_r$, resulting in:

$$I(t) = \phi(t) E_v(t) \quad (3)$$

$$R_t(t) = R_0 * (1 - \phi(t) E_v(t)) * (1 - E_R(t)) \quad (4)$$

The condition for a decreasing infection rate is $R_t(t) < 1$ and the equilibrium level is $R_t(t) = 1$. If the latter condition is inserted in Equation 4, the equation for the required equilibrium fraction of vaccinated and recovered person's ϕ_{Eq} becomes:

$$1 = R_0 * (1 - \phi_{Eq}(t) E_v(t)) * (1 - E_R(t)) \quad (5)$$

$$\phi_{Eq}(t) = \left(1 - \frac{1}{R_0(1 - E_R(t))} \right) \frac{1}{E_v(t)} \quad (6)$$

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This relatively uncomplicated expression is useful for rapidly predicting the required fraction of vaccination in a population, both for COVID-19 and other pandemic infections. Since the model uses an average R-number for the whole population, it is conservative and rather overestimates than underestimates the required vaccination rates [1]. (People with many contacts typically become infected early in a pandemic, which lead to overestimated average transmission coefficients.)

As complement and validation for the modeling, data for COVID-19 incidence as function of vaccination fraction was collected from public sources for different European countries and regions 19-26 November 2021.

Results and Discussion

To predict how large fraction of the population that must be vaccinated and how strong restrictions that must be maintained to cease the pandemic, Equation 6 was plotted as function of basic reproduction number R_0 , vaccine efficacy, and restriction efficiency (Figure 1).

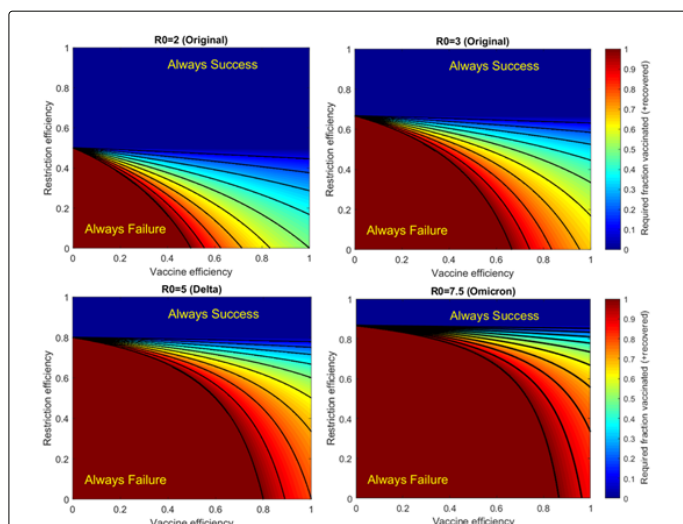


Figure 1: Heat maps showing required vaccination rate as function of restriction efficiency and vaccine efficiency for different basic reproduction ratios R_0 . The color indicates required vaccine rate, with black lines in steps of 10%. The original COVID-19 has $R_0=2-3$, Delta $R_0 \approx 5$ and Omicron $R_0 \approx 7.5$.

The original COVID-19 virus has R_0 around 2-3 [4,5], Delta $R_0 \approx 5$ [5] and Omicron $R_0 \approx 7.5$ [5,6]. The basic reproduction number increases with increasing population density, and it becomes higher during the winter (on the northern hemisphere), probably because of lower humidity, less sunshine and more indoor activities.

The efficiency of today's vaccines is lower against Omicron than against Delta and the ancestral COVID-19 virus. For Pfizer (BNT162b2), the efficacy is 88.2% and 88.0% against Delta and Omicron, respectively, 2-9 weeks after dose 2 [7]. The efficacy drops to 64.8% and 36%, 20-24 weeks after dose 2. A third dose increases the efficacy (after 2 weeks) to 92.6% and 75.5%, respectively. Similar trends were found for AstraZeneca (ChAdOx1-S with BNT162b2 booster-dose) [7] and Moderna (mRNA-1273) [8] and 75.5%, respectively. Similar trends were found for AstraZeneca (ChAdOx1-S with BNT162b2 booster-dose) [7] and Moderna (mRNA-1273) [8]. For the original COVID-19 variant, with basic reproduction number R_0 around 2-3 and a vaccine efficacy around 80-90% (2 doses), Figure 1 indicates that medium-strong restrictions (50-70%) or a vaccination rate around 70% is sufficient to halt the pandemic. This has been confirmed empirically in

many countries, both for the original COVID-19 virus and e.g., for the Alpha (B.1.1.7) and Beta (B.1.351) variants of concern.

For the Delta version, with $R_0 \approx 5$ and vaccine efficiency around 65%-90% (2 doses), very high vaccination rates ($\sim 90\%$), very strong restrictions (80%), or a combination of medium high restrictions (50%-60%) and vaccination rates (70%) are required. This prediction is confirmed e.g., by the observation that the partial lockdown in Germany December 2021 succeeded to stop the Delta wave under these conditions.

For the Omicron version, with $R_0 \approx 7.5$ and vaccine efficiency around 0%-88% (2 doses) or 54.6%-75.5% (3 doses), extremely strong restrictions (90%) or a combination of strong restrictions (70%-80%) and a high vaccination rate with three doses (70%-85%) is required.

Note that the required vaccination rate in Figure 1 is the combined fraction of vaccinated or recovered persons. Even if the vaccination/restriction strategy fails, the transmission will stop when enough people have been infected and recovered, but to a larger cost in human lives and suffering. A high vaccination rate is strongly desired because it reduces both the virus transmission and the risk for serious health effects for the infected individuals. Although the hospitalization probability for Omicron is 40%-45% lower than for Delta, it is still high [9].

To confirm the modeling results, data for COVID-19 incidence and vaccination rate was collected 19-26 November 2021 for countries in Europe and regions in Germany and the Czech Republic. Data was mainly retrieved before the partial lockdown in Germany, which started 24th November. The 7-incidence (per 100 000) clearly decreased with increasing vaccination rate (Figure 2). A triangular pattern is evident, indicated by two enveloping black dashed lines. The logic behind these lines is that each country, city, or region has a specific reporting/testing procedure, resulting in different degrees of underreporting. Therefore, a huge scatter is evident for low or moderate vaccination rates. When approaching a specific rate of vaccination, the scatter must be smaller and reach (almost) zero. Thus, the two dashed lines must have a common intersection with the x-axis, and this point is the required vaccination rate to halt the pandemic.

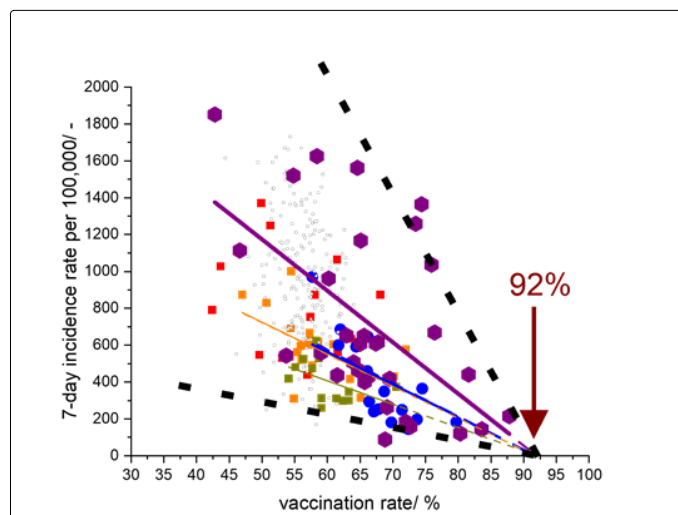


Figure 2: COVID-19 7-day incidence rate per 100,000 versus vaccinate rate (2 doses) for 6 geographical regions, showing that a vaccination rate of ca. 92 % was required to cease the Delta variant with limited restrictions in Europe late November 2021. The choice of vaccine, the number of doses, the season, the time since the last dose and the currently dominating COVID-version strongly affect the number. **Note:** (■) Saxony (districts), (■) Saxony-Anhalt (districts), (■) Thuringia (districts), (●) Germany (states), (●) Czech Republic (municipals), (●) European countries.

The data indicates that a vaccination rate around 92% (2 doses) would have been sufficient to suppress the pandemic in Europe late November 2021, without serious restrictions. At that time, the Delta (B.1.617.2) variant of concern was dominant. Since the required vaccination rate is affected by season, currently dominant Covid variant, typical vaccine-type [10], average time since the last dose, maximum number of doses etcetera, the value of 92% is obviously not generally applicable. In December 2021, during the partial lockdown in Germany, the German incidence decreased, indicating that those restrictions were sufficient to halt the Delta-virus at a vaccination level around 70% (2 doses). The currently dominating Omicron (B.1.1.529) variant of concern is however more infectious and requires stronger measures to quench. All these results agree with the modeling predictions.

Conclusion

An epidemiological equilibrium model was applied to predict required vaccination rate and/or required amounts of restrictions as function of (empirically known) vaccine efficiencies and basic reproduction numbers (R_0). The model indicates that for the Omicron (B.1.1.529) variant of concern, a combination of strong restrictions (70%-80%) and high vaccination rates (70-90%) with three doses of e.g. the Pfizer (BNT162b2) vaccine will be required; otherwise a large proportion of the population will be infected. Tailor-made updates of the vaccine will probably be needed to stop the pandemic completely without maintaining relatively severe restrictions or without accepting that large fractions of the population become infected. It is strongly recommended to rapidly encourage a high (3-dose) vaccination rate, because that will decrease both the virus transmission and the severity of the infections. For the Delta (B.1.617.2) variant of concern, our data (empirical and model predictions) indicate that a vaccination (and/or recovery) rate of ~ 92% (2 doses) is sufficient for stopping the pandemic without serious restrictions, under conditions like those in Europe late November 2021.

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