Vaccination strategies in structured populations under partial immunity and reinfection

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The enormous effects of infectious diseases in humankind through history could only be counteracted through massive vaccination campaigns. Optimal protocols of vaccine administration to minimize the effects of infectious diseases depend on several variables that admit different degrees of control: the characteristics of the disease and its impact on different groups of individuals, controlled non-pharmaceutical interventions and, critically, vaccine roll-out [1]. It is often very difficult to assess *a priori* the importance and effect of such different factors.

Here we study a compartmental model of infection propagation and analyse the effect that variations in the vaccination and reinfection rates have on the progression of the disease and on the number of fatalities [2]. The model considers five different classes: Susceptible (S), Infected (I), Reinfected (Y), Recovered (R) and Dead (D), and fulfills

$$\dot{S} = -\beta_{SI}\frac{IS}{N} - \beta_{SY}\frac{YS}{N} - v\,\Theta(S,\theta) \quad (1)$$

$$\dot{I} = \beta_{SI}\frac{IS}{N} + \beta_{SY}\frac{YS}{N} - rI - \mu_I I \quad (2)$$

$$\dot{Y} = \beta_{RI}\frac{IR}{N} + \beta_{RY}\frac{YR}{N} - rY - \mu_Y Y \quad (3)$$

$$\dot{R} = rI + rY - \beta_{RI}\frac{IR}{N} - \beta_{RY}\frac{YR}{N} + v\,\Theta(S,\theta) \quad (4)$$

$$\dot{D} = \mu_I I + \mu_Y Y, \quad (5)$$

where $\Theta(S,\theta)$ is a function taking into account the maximum fraction of population vaccinated. For simplicity, we take here a step function at 70% vaccination. Parameters refer to the infection rate (β, subindexes representing the two classes in contact), the recovery rate r and the death rate for first and secondary infections (μ_I and μ_Y, respectively). Details in estimated values can be found in [2].

As a practical example, we study COVID-19 dynamics in various countries using real demographic data and contact matrices between different groups [3]. We first divide the population into two age groups to highlight the overall effects on disease caused by vaccination rates and demographic structure. We observe, first, that the higher the fraction of reinfected individuals, the higher the likelihood that the disease becomes quasi-endemic and, second, that optimal vaccine roll-out depends on demographic structure and disease fatality. Therefore, there is no unique vaccination protocol, valid for all countries, that minimizes the effects of a specific disease.

Our second analysis focused on the dynamics of COVID-19 in Spain using nine age groups. We explored the space of all possible combinations (9!) for the order in the vaccination protocol as a function of age and evaluated its performance in terms of the number of fatalities and infections, comparing with the baseline case of vaccination in strict decreasing age order. We conclude that, at least for COVID-19 in Spain, there is no strategy significantly better than age-ordered vaccination.

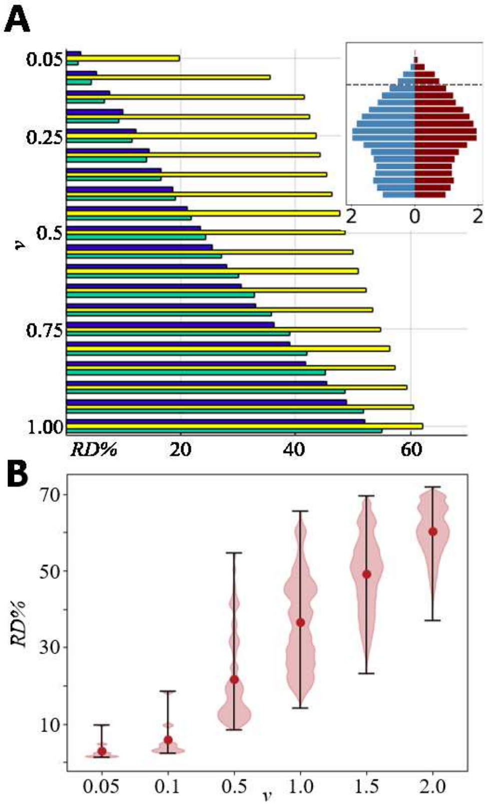

Fig. 1. Death reduction (RD%) in Spain as a function of vaccination rate (v) compared to the no vaccination scenario for (A) the 2-group model with an age threshold at 80 years considering old-first (yellow), young-first (dark blue) and simultaneous (turquoise) vaccination. (B) the extended 9-group model. Violin plots summarize the distribution of all possible permutations.

[1] J. Lavine, O. Bjornstad, and R. Antia, *Immunological characteristics govern the transition of COVID-19 to endemicity*, Science (2021).

[2] G. Rodríguez-Maroto, I. Atienza-Diez, S. Ares and S. Manrubia, *Vaccination strategies in structured populations under partial immunity and reinfection*, MedRxiv (2021).

[3] D. Mistry, M. Litvinova, AP. Piontti, M. Chinazzi, L. Fumanelli, MFC. Gomes et al., *Inferring high-resolution human mixing patterns for disease modeling*, Nature Communications (2021).