The vaccination dilemma: A mean field analysis

Benjamin Steinegger[1], Alessio Cardillo[2,3], Paolo De Los Rios[1], Jesús Gómez-Gardeñes[3,4], and Alex Arenas[5]

[1]Laboratory for Statistical Biophysics, École Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland
[2]Institut Català de Paleoecologia Humana i Evolució Social (IPHES), E-43007 Tarragona, Spain
[3]GOTHAM Lab, Institute for Biocomputation and Physics of Complex Systems (BIFI), University of Zaragoza, E-50018 Zaragoza, Spain
[4]Department of Condensed Matter Physics, University of Zaragoza, E-50009 Zaragoza, Spain
[5]Department d'Enginyeria Informática i Matemátiques, Universitat Rovira i Virgili, E-43007 Tarragona, Spain

Vaccination, whenever possible, is the most effective way to harness and prevent the spreading of a disease. Besides the protection bestowed at individual level, vaccination hinders as well the spreading at whole population level. Optimally, the individual decisions to vaccine would lead to the immunization of the entire population. However, instead of taking the vaccine, individuals may also rely on the others will to vaccinate. However, if too many of these *free riders* are present in the population, herd immunity is lost. This social *dilemma* characterizes the voluntary vaccination problem.

For analyzing social dilemmas, game theory is an adequate tool. Previous studies have combined game theory and epidemic spreading, developing coevolutionary models, in order to study the vaccination uptake [1]. Nevertheless, the analytical work has mainly focused on vaccination against pediatric diseases, such as measles, for example. In contrast, most of the articles having tackled the vaccination uptake against the seasonal influenza relied heavily on numerical simulations [2, 3, 4, 5], which makes it difficult to understand the underlying processes. For this reason, we set up a model incorporating the main features of the previous work, but that in addition allows for an analytical mean field solution [6].

The model is organized in the following way. We consider the fraction of infected agents in the previous year's influenza outbreak as an input of the model. From there, we set up a vaccination game, whose stationary state will define the vaccination coverage of the population. A subsequent outbreak of the disease with transmission probability β is then considered in the population. We obtain analytical expressions for the vaccine coverage y^* and the epidemic thresholds.

A crucial property of vaccines against the seasonal influenza is their effectiveness. The constant mutation of the virus strains makes it difficult to anticipate the subsequent season's form of the virus. Vaccine efficiency is usually only between 30% and 60%. Interestingly, the system shows a big tolerance regarding the vaccine quality, γ. As a matter of fact, a decrease in the effectiveness of the vaccine can even promote vaccination as one can see in Fig. 1. At first glance, the increase in vaccine uptake as effectiveness decreases may seem counterintuitive. However, this phenomena stems from the fact that the probability of getting infected becomes non negligible. In other words, as the vaccine efficiency decreases there is a competition between the increasing risk of getting infected and the reduced protection bestowed by the vaccine itself. Furthermore, we are able to show that the maximal vaccination coverage is reached when a further decrease in the vaccine effectiveness increases the infection probability by a larger amount for vaccinated than for not vaccinated agents. Hence, what may look as an irrational act at first sight is —instead— a rational individual decisions of agents striving to mitigate the infection pressure. In this sense, the corresponding effectiveness of the vaccine $(1-\gamma)$ as the maximal vaccine coverage $y^*_{\max}$ is reached, may be seen as a tolerance threshold of the system.

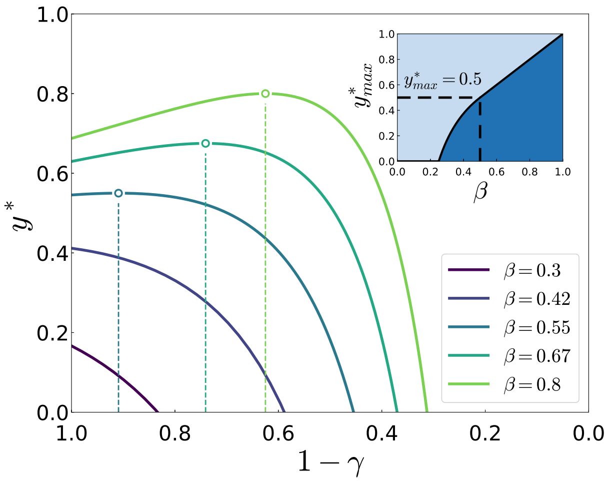

Fig. 1. Vaccination coverage at equilibrium y^* as a function of vaccine effectiveness $(1-\gamma)$. A perfect vaccine corresponds to $\gamma = 0$. Each line represents a different value of infection probability β. The maximum coverage $y^*_{\max}$ is denoted by a point and the dashed line delimits the tolerance range. The inset presents the maximum coverage $y^*_{\max}$ as a function of infectivity β. The color highlights the region where vaccination takes place or not.

Additionally to the high relevance of vaccine effectiveness in the voluntary vaccine uptake, we are recently witnessing the emergence of widespread anti-vaccine movements, which are mainly fueled by misconceptions and mischievous news about vaccines. A way for incorporating these movements in the model is the introduction of *zealots*; agents who unconditionally do not take the vaccine. Interestingly, the presence of the zealots has a non trivial detrimental effect on the aforementioned tolerance to decreasing vaccine quality.

[1] Z. Wang, C. T. Bauch, S. Bhattacharyya, A. d'Onofrio, P. Manfredi, M. Perc, N. Perra, M. Salathé, and D. Zhao, Phys. Rep. **664**, 1-113 (2016).

[2] F. Fu, D. I. Rosenbloom, L. Wang, and M. A. Nowak, Proc. R. Soc. B **278**, 42-49 (2011).

[3] B. Wu, F. Fu, L. Wang, PLoS ONE **6**, e20577 (2011).

[4] A. Cardillo, C. Reyes-Suárez, F. Naranjo, and J. Gómez-Gardeñes, Phys. Rev. E **88**, 032803 (2013).

[5] L. G. Alvarez-Zuzek, C. E. La Rocca, J. R. Iglesias, and L. A. Braunstein PLoS ONE **12**, e0186492 (2017).

[6] B. Steinegger, A. Cardillo, P. De Los Rios, J. Gómez-Gardeñes, and A. Arenas, Phys. Rev. E **97**, 032308 (2018).