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Effect of vaccination strategies on the dynamic behavior of epidemic spreading and vaccine coverage

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ABSTRACT

The transmission of infectious, yet vaccine-preventable, diseases is a typical complex social phenomenon, where the increasing level of vaccine update in the population helps to inhibit the epidemic spreading, which in turn, however, discourages more people to participate in vaccination campaigns, due to the "externality effect" raised by vaccination. We herein study the impact of vaccination strategies, pure, continuous (rather than adopt vaccination definitely, the individuals choose to taking vaccine with some probabilities), or continuous with randomly mutation, on the vaccination dynamics with a spatial susceptible-vaccinated-infected-recovered (SVIR) epidemiological model. By means of extensive Monte-Carlo simulations, we show that there is a crossover behavior of the final vaccine coverage between the pure-strategy case and the continuous-strategy case, and remarkably, both the final vaccination level and epidemic size in the continuous-strategy case are less than them in the pure-strategy case when vaccination is cheap. We explain this phenomenon by analyzing the organization process of the individuals in the continuous-strategy case in the equilibrium. Our results are robust to the SVIR dynamics defined on other spatial networks, like the Erdős–Rényi and Barabási–Albert networks.

1. Introduction

Throughout history, many diseases which had swept the whole globe, such as Black Death (Plague) and smallpox, are kept within limits by human. Vaccination plays a very important role against these terrible epidemic diseases. In 2002, Severe Acute Respiratory Syndromes, a newly and seriously disease, broke out and spread to all over the world very quickly [1,2]. The pathogenesis was studied and the corresponding vaccine was developed by scientists and experts in a very short time [3,4]. Recently, some scientists believe that the hope of universal influenza vaccines has become more tangible than ever before [5–8].

It is commonly believed that the compulsory vaccination is difficult to be performed for some social factors, such as religious belief and human rights, etc. Some researches turn to study the dynamical behavior of voluntary vaccination program and present a series of significant results over the past few years [9–24]. For example, Bauch et al. used game theory to explain the relationship between group interest and self-interest in smallpox vaccination policy [9–11] and found that voluntary vaccination was unlikely to reach the group-optimal level. Blower et al. found that universal long-term flu vaccine may not prevent severe epidemic [12], and then investigated the effect of voluntary vaccination on the prevalence of influenza based on minority game theory and showed that severe epidemics could not be prevented unless vaccination programs offer incentives [13,14]. Chen et al. studied a SEIRS epidemic disease model with two profitless delays and vertical transmission, and analyzed the dynamics

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behaviors of the model under pulse vaccination [15,16]. Zhang and Fu et al. proposed a game-theoretic model to study vaccination dynamics on classical networks, including well-mixed population, square lattice, Erdős–Rényi (ER) network and Barabási–Albert (BA) network [17–19]. They found that the population structure behaves as a 'double-edged sword' for public health. Zhang investigated the impact of the other-regarding behavior in individuals' decision making about vaccination dynamics [21]. Recently, Wu and Zhang incorporated the impact of peer pressure into vaccination dynamics, and they found that the peer pressure is also a double-edged sword, which can strongly promote vaccination when its cost is below a critical value, but can strongly impede it if the critical value is exceeded [22].

In most previous studies, the vaccination strategy of every individual is assumed to be pure, i.e. either vaccinate or not vaccinate during the vaccination campaign [17–22,25]. As we know, there exists a critical vaccination level in the population such that: if the vaccine coverage is below the vaccination level, an epidemic will occur, otherwise epidemics will be prevented. Based on self-interest, a few studies consider that the action of vaccination is expressed in probability [12–14]. We call the two cases as pure-strategy case and continuous-strategy case. In the present work, we intend to study how the vaccination dynamics is affected by the two types of vaccination strategy. Our results presented below show that both the final vaccine coverage and the final epidemic size in the continuous-strategy case are less than that in the pure-strategy case in spatial network when the cost for vaccination is low. Furthermore, the impact of the strategy-mutation mechanism on dynamic behavior of epidemic spreading and vaccine coverage is also briefly investigated in the continuous-strategy case.

2. Model

Following previous studies [19,20], we model the vaccination dynamics as a two-stage, vaccination-stage and epidemic spreading-stage, with a mutual feedback form (see Fig. 1). In the vaccination-stage, there is a vaccination campaign, each individual decides whether or not to get vaccinated. To get vaccinated will incur a cost C_V and the vaccine gives perfect immunity to the infectious disease. The cost C_V includes the immediate monetary cost for vaccine and the potential risk of vaccine side-effects. For the pure-strategy case, there are two strategies, to vaccinate or not to vaccinate. For simplicity and efficiency but without loss of generality, we focus on the discretization of continuous strategies in the continuous-strategy case, that is, the individual i can choose a strategy x_i from a strategy set $\{\frac{0}{100}, \frac{1}{100}, \cdots, \frac{100}{100}\}$, where the value of x_i denotes the vaccination probability of individual i [26] (we have checked that our results presented below remain the same when the vaccination probabilities of the individuals take continuous real values in the range $[0, 1]$). In the epidemic spreading-stage, the epidemic strain infects an initial number of individuals I_0 (1‰ of the population size) and then spreads in the population according to the classical susceptible-infected-recovered (SIR) epidemiological model [27,28], with per-day transmission rate r for each pair of susceptible-infected (SI) contact and recovery rate g for each infected (I) individual getting immune to the disease. The epidemic continues until there are no more newly infected individuals. At this moment, those unvaccinated and uninfected individuals are called free-riders, owning to the fact that they are successfully escaped from the spreading season and pay for nothing. Meanwhile, those unvaccinated and infected individuals incur a cost C_I, which may account for disease complications, expenses for treatment, etc. The final epidemic size and the final vaccination level are decided by the rescaled parameter $c = C_V/C_I$, whose value is restricted in the region of $[0, 1]$ (otherwise, doing nothing would be better than getting vaccinated).

At the end of each epidemic spreading season (i.e., before the next two-stages for vaccination and disease spreading), all individuals will update their vaccination strategy by a Fermi function-like rule before the new epidemic season starts. The individual i chooses an individual j randomly from one's immediate neighborhood to compare their cost (or payoff) and then adopts the vaccination strategy of j with a probability dependent on the payoff difference [29–32]. Generally speaking, it would be more

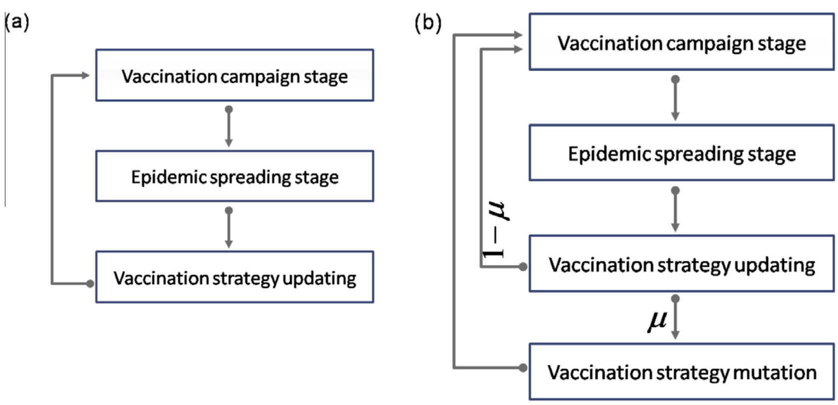

Fig. 1. Schematic illustration of the simulation process of vaccination dynamics. The simulation process (a) applies to the pure-strategy case and the continuous-strategy without mutation case, and the simulation process (b) applies to the continuous-strategy with mutation case. μ is the mutation probability. More detailed description about vaccination-stage, epidemic spreading-stage, update, and mutation see article.