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Evolutionary vaccination dynamics with internal support mechanisms

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HIGHLIGHTS

- The two internal support mechanisms can effectively improve the vaccine coverage.
- Vaccine coverage is still high when the relative cost for vaccination is close to 1.
- The local support mechanism in heterogeneous networks is robust to the general case.
- The stochastic algorithm is faster than the classic Gillespie's algorithm.

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ABSTRACT

This paper reports internal support mechanisms (i.e., without external intervention) to enhance the vaccine coverage in the evolutionary vaccination dynamics. We present two internal support mechanisms, one is global support mechanism in which each individual pays a support cost to build up a public fund and then the public fund is divided by all vaccinated individuals, while another is local support mechanism in which each individual pays a support cost and then this support cost will be divided by its immediate vaccinated neighbors. By means of extensive computer simulations, we show that, in the same strength of support cost, the heterogeneous (local) support mechanism can encourage more people to take vaccination than the homogeneous (global) support mechanism. And then, we study the most general case that includes supporters and troublemakers together, where supporters (troublemakers) mean that the individuals join (do not join) the internal support mechanism, in the population. We surprisingly find that, in scale-free networks, the voluntary vaccination dynamics with the local support mechanism will not degrade into the original voluntary vaccination dynamics, and the vaccination level can still be effectively improved. In view of most social networks are of scale-free degree distribution, we study further in empirical networks and find that the vaccination level can still be improved in the absence of external intervention.

1. Introduction

Vaccination is an important and effective measure for the corresponding infections disease prevention, control and even eradication in local or global population. It cannot only protect the vaccinated individuals themselves from catching the disease, but also reduce the risk of infection to immediate unvaccinated neighbors directly and to others unvaccinated individuals of the whole population indirectly. As we all know, epidemics will not break out when vaccine coverage reaches

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the critical vaccination level in the population. For example, it is well known that smallpox [1] and rinderpest [2] were officially declared eradicated in 1979 and 2011, respectively. However, compulsory vaccination is limited by many social factors, such as religious belief and human rights, and almost cannot be implemented [3]. Moreover, due to various condition such as risk of infection, prevalence of disease, vaccine coverage, and cost of vaccination, voluntary vaccination often cannot result in sufficiently strong herd immunity for disease eradication [4].

Achieving widespread vaccine coverage by voluntary vaccination is a major challenge for public health administration and practice. In the last decade, some researchers turned to study the impact of the individual behavior on voluntary vaccination dynamics [5–14]. For example, Bauch et al. used game theory to explain that voluntary vaccination was unlikely to reach the group-optimal level [5]. Vardavas et al. found that universal long-term flu vaccine may not prevent severe epidemic [6], and 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 [7,8]. Perisic et al. assumed the vaccine is free and imperfect efficacy (like the WHO smallpox eradication program), and reported that, in social contact networks, disease can be eradicated under voluntary vaccination [9]. Cornforth et al. studied the voluntary vaccination behavior in different contact networks and found that a vaccination rate cycle: a severe epidemic in one year inspires high vaccination rates, and this causes a milder epidemic which then leads to lower vaccination rates in the following year, and then causes a severe epidemic in the following year [10]. Fu et al. [11] and Fukuda et al. [12] used different risk assessment model in a vaccination game where an individual updates his/her strategy to observe the voluntary vaccination behavior.

Recently, Zhang et al. studied two kinds of typical subsidy policies by external intervention, free subsidy policy and partial-offset subsidy policy, and found that the partial-offset subsidy policy encourages more people to take vaccination and a moderate subsidy policy rate in the partial-offset scenario for each vaccinated individual can guarantee the group-optimal vaccination [13,14]. As we know, the opportunity of subsidy from external intervention is usually hard to come by. So, in this paper, we intent to find a way of internal support to improve the vaccine coverage in the population. It is well known that individuals are rational and emotional, which means that they always eager to obtain the maximal profit under the existing rules and sympathetically help others in trouble in the case of spare capacity. Based on this opinion, we propose two internal support mechanisms to the evolutionary vaccination dynamics, one is global support mechanism in which each individual pays a support cost to build up a public fund and then the public fund is divided by all vaccinated individuals, while another is local support mechanism in which each individual pays a support cost and then this support cost will be divided by its immediate vaccinated neighbors. Our results presented below show that the vaccine coverage can be improved notably and the local support mechanism is more efficiently than the global support mechanism in the same strength of support cost.

The rest of the paper is organized as follow: In Section 2, we define our model and give detailed information for the numerical simulation method and the parameterizations. In Section 3, we present and analyze the main results of our model. In Section 4, we discuss the results and conclude the paper.

2. Model

We study the impact of voluntary vaccination with the internal support mechanisms on epidemic dynamics taking place on networks. Following previous studies [11,15], we model the dynamical process as two stages, i.e., the vaccination decision process with internal support mechanism and the epidemic spreading process. The original vaccination dynamic process is as follow: during the vaccination decision process without internal support mechanism, each individual decides whether or not to get vaccinated in a vaccination campaign, and then each vaccinated will incur a cost C_V and get immune to the disease; during the epidemic spreading process, considering the usual susceptible–infected–recovered (SIR) [16] epidemic process with transmission rate r for per susceptible–infected contact and recovery rate g for per infected individual, those infected individuals will incur a cost C_I. Without loss of generality, we set $c = C_V/C_I$ and $C_I = 1.0$. Also, the efficacy and effectiveness of a vaccination are not always perfect for some infectious diseases in reality [17,18] and the voluntary vaccination dynamics will be more complicated [4,19]. However, as we know, it has a complete set of stages before launch a vaccine product, such as clinical validation and sampling test. In a general way, the efficacy of vaccine is always very high [9]. For the sake of simplicity, we assumed that vaccinated individuals get perfect immunity against a seasonal infectious disease during an epidemic season in this paper.

We know that, from global perspective, vaccination can hinder disease spreading in whole population system, while from local perspective, individuals will reduce the infected risk by their vaccinated neighbors. Here, we consider two internal support mechanisms adding to the vaccination decision process: one is called global support mechanism, each individual pays a support cost $a * c$, where a denotes the strength of support and $a \in [0, 1]$, to build up a public fund, and then the public fund will be divided by all vaccinated individuals; another is called local support mechanism, each individual i pays a support cost $a * c$ and this cost will be divided by its immediate vaccinated neighbors (if all neighbors of individual i are unvaccinated, individual i will not pay the cost). In the global support mechanism, unvaccinated and healthy individuals just pay a support cost $a * c$; infected individuals pay both support cost and infected cost 1; for vaccinated individuals, the payoff consists of three parts: the vaccinated cost c, the support cost, and the vaccinated subsidy from support mechanism $a * c/f_V$, where f_V is the vaccine coverage in the whole population. In the local support mechanism, it is different from the global support mechanism in support cost and vaccinated subsidy. The support cost of individual i is $a * c$ (or 0) when the