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A new prediction model of infectious diseases with vaccination strategies based on evolutionary game theory

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ABSTRACT

Infectious diseases have proven to be remarkably resilient foes of human health and so the prevention and control of infectious diseases have been attracting the attention of all countries over the world. Vaccination is an effective way to prevent the spread of infectious diseases. However, vaccination is a long-standing social dilemmas due to the vaccine's risk by itself and the spread of infectious diseases in the population depends on not only the pathogen itself, but also the impact of social network structures. In this paper, we propose a new prediction model of infectious diseases with new vaccination strategies based on network structures and dynamic replicator. In our model, we consider not only the subsidies of vaccine failure but also the incentive strategy for medical treatment to promote individuals to take the initiative to vaccinate. At the same time, in decision-making phase, we use weighted average benefits of all participants to update their strategies due to individual difference. Simulation experiments show that the our proposed model is much effective and better than other existing models. We also use Jacobian matrix to prove the stability of dynamic equilibrium for our proposed model.

1. Introduction

Infectious diseases caused considerable damage to human societies. Many of these diseases, such as measles, pertussis, influenza, and many others, have been burdening us for centuries, while new infectious diseases, such as Ebola, Zika virus, and SARS, continue to emerge from animal populations and make the jump to human populations, or spreading to new human populations due to climate change or other anthropogenic disturbances. To help reduce their impact, a lot of mathematical models and methods of disease transmission have been studied to understand disease dynamics and inform prevention strategies [1]. Preemptive vaccination is one of the most important preventive measures of modern times for preventing epidemics of infectious diseases, as well as reducing morbidity and mortality [1–3]. As the vaccination level increases and herd immunity is achieved, no one can be infected. Thus, these vaccinated individuals can help the unvaccinated ones escape infection. So, the unvaccinated people avoid the side effects from vaccination and also save the cost of vaccination. As a consequence, many people decide to no longer vaccinate, and thus to effectively free-ride on the efforts of others who still vaccinate their offspring [1,4]. Thus, under voluntary vaccination policy, people may consider various factors (such as the cost of vaccination, self-interest, vaccine risk by itself, and the vaccination behaviors of other individuals [5–7] not to choose vaccination. With such behavior on the uprise, the herd immunity gets lost and the probability for the outbreak of diseases increases significantly. On the other hand, compulsory vaccination may result in the infringement of civil rights [8]. Thus it is very hard to protect populations from epidemics [9,10]. Another important and difficult factor in eradicating vaccine-preventable disease is an inherent paradox in epidemiology [1,4,11]. Therefore, to measure effective public health for preventing epidemics of infectious diseases, we need to study these interrelations among vaccination coverage, prevalence of disease and vaccination behaviors, and develop dynamic and quantitative models for predicting the consequences of these complex interrelations. In this paper, we will try to do some exploration about this aspect.

In order to study the vaccination dilemma, game theoretic frameworks have been applied to the population in which each individual tries to maximize her own payoff. Game theoretical models of interactions between vaccinating behavior and disease dynamics typically define strategies (such as vaccinator or

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non-vaccinator), define payoffs for those strategies, and attempt to solve for a Nash equilibrium. Note that the payoff for those strategies chosen by individuals depends on the strategies adopted by others in the population. Many authors are interested in it and obtain a lot of research results [1,3,4,11–19]. For example, Wang et al. [1] reviewed the developmental arc of theoretical epidemiology with emphasis on vaccination, as it led from classical models assuming homogeneously mixing (mean-field) populations and ignoring human behavior, to recent models that account for behavioral feedback and/or population spatial/social structure. Bauch and Earn [18] assumed that individuals acted with perfect information on their probability of getting infected. However, classical game theory may not be well suited to describe real-world vaccinating behavior. It assumes that individuals are selfishly rational optimizers. But, in fact, effects like social learning, bounded rationality, and imperfect information are very important in vaccinating decisions [20], and this can impact predicted behavior [14]. Moreover, individuals cannot get perfect information, but always update their strategies by imitating those who gain the high payoff [11,12,17,21]. Thus Bauch [17] used the imitation behavior of those facing disease outbreaks to characterize adaptive vaccination behavior, and demonstrated that this imitation behavior can produce an oscillation in disease outbreaks. In [17] and [21], an individual *P* always compare her payoff with the one of one randomly selected neighbor *Q*. If *Q* succeeds in earning a higher payoff than *P* in the last epidemic season, then *P* may, with higher probability, imitate *Q*'s strategy in current epidemic season. But, from [11] and [1], we see that individuals update their strategies with the probability based on an average payoff of their neighbors who choose the same strategy individuals, but not relying only on the payoff of one neighbor. In addition, many other factors [1,3,22] may also influence individuals' choice. For example, mass mediae (such as television, radio, and newspaper) have great power to influence the behavior of the people and to present objective information about any currently spreading diseases. Perc et al. [3] reviewed experimental and theoretical research that advances the understanding of human cooperation, focusing on spatial pattern formation, on the spatiotemporal dynamics of observed solutions, and on self-organization that may either promote or hinder socially favorable states.

However, most studies have not considered the effects of interactions between network structure and individual learning behavior, and assume that the population is homogeneously mixed and that individuals are fully rational such that they make decisions to pursue maximum personal utility based on their perceived risks. In reality, there is always a spatial structure on which both the disease transmission and individual contacts take place. Individuals may be limited rational. Under heterogeneous network, the influence of everybody is different. Han and Sun [23] explored an evolutionary vaccination game in the network by considering the closeness. Their simulation results in [23] showed that the closeness may have an active role in weakening both the spreading of epidemic and the vaccination. Therefore, it is necessary to focus on epidemics spreading in contact networks. As we know, in real world, famous individuals (such as movie stars and professional stars) have more influence for vaccination choice than ordinary persons. Thus, in this paper, we propose a new model with weighted average payoff, in which an individual considers the effects of interactions between network structure and individual learning behavior. In our model, we define a new strategy mechanism for updating strategy. That is, an individual *i*

(1) randomly selects one individual *j* with strategy s_j;
(2) gets all individuals who select s_j as their strategy and then calculates their weighted average payoff based on the network structure and individual difference;
(3) compares her own payoff with this weighted average payoff.

Thus, the individual *i* updates his strategy with the probability $p = min\{1, \frac{s}{t}\}$, where *s* is her opponent's payoff and *t* is the weighted average payoff by averaging payoffs of whom adopt the same strategy as her opponent. But the individual *i*'s strategy is not based on the payoff of a certain opponent among her neighbors. In the following, we will analyze the effectiveness of this new strategy-updating rule on vaccination coverage and on the final proportion of the population that becomes infected.

Besides, note that previous work usually assumes perfect vaccination. That is, the vaccinated individuals gain perfect immunity against the disease [24]. The effectiveness of vaccination, however, is not 100%, such as measles [25], malaria [26] and HIV [27]. Even though the actual vaccination is perfect, the perceived effectiveness can be not perfect. In fact, it has been shown that the perceived effectiveness is often lower than the actual one in [28]. Therefore, imperfect vaccination [29] is taken into account in our proposed model. In our model, we consider the vaccination failure, if an individual is infected by the disease though he get vaccinated, then he will get subsidies in the treatment.

The main contributions of this paper are as follows:

(1) The spread of infectious diseases in the population depends on not only the pathogen itself but also the impact of social network structure. Different network structures have a great impact on the spread of infectious diseases and so need to be considered in the prediction model. Thus we propose a new prediction model of infectious disease with new vaccination strategy based on network structures and dynamic replicator.
(2) We propose a new incentive strategy for vaccination failure and treatment. In our model, we consider not only the subsidies of vaccine failure but also the incentive strategy for medical treatment to promote individuals to take the initiative to vaccinate.
(3) In decision-making phase, the traditional approach is to randomly select one individual from her neighbors, compare the two payoffs, and then update their strategy. In this paper, as we said before, we propose a new mechanism that we randomly choose an individual from her neighbors and get her strategy, calculate the weighted average value of the benefits of all participants who choose this strategy by considering the individual's difference in heterogeneous network, last compare the two payoffs.
(4) We use mathematical analysis and Jacobian matrix to show the stability of dynamic equilibrium for our model.
(5) Our experimental results show that our proposed model is effective and is better than other existing models (such as MED [11] and FTA [23]).

The remainder of this paper is organized as follows. In Section 2, we describe the details of our proposed framework, which combines the epidemiological dynamics by considering the network structure and a decision-making process with regard to the vaccination (vaccination game), as well as the method of our computational simulation. On this basis, in Section 4 , we show the results of evaluation experiments and the analyses for these results. Conclusions and suggestions for future research are discussed in Section 5.

2. Our models and methods

Our model contains two stages (see Fig. 1). The first stage is vaccination campaign for decision making. Each individual in the population (a node on social networks) makes her decision whether to get vaccinated based on her strategy.

The second stage corresponds to an epidemic season. For describing epidemiologic dynamics on a structured population, our