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Positive and negative effects of social impact on evolutionary vaccination game in networks

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ABSTRACT

Preventing infectious disease like flu from spreading to large communities is one of the most important issues for humans. One effective strategy is voluntary vaccination, however, there is always the temptation for people refusing to be vaccinated because once herd immunity is achieved, infection risk is greatly reduced. In this paper, we study the effect of social impact on the vaccination behavior resulting in preventing infectious disease in networks. The evolutionary simulation results show that the social impact has both positive and negative effects on the vaccination behavior. Especially, in heterogeneous networks, if the vaccination cost is low the behavior is more promoted than the case without social impact. In contrast, if the cost is high, the behavior is reduced compared to the case without social impact. Moreover, the vaccination behavior is effective in heterogeneous networks more than in homogeneous networks. This implies that the social impact puts people at risk in homogeneous networks. We also evaluate the results from the social cost related to the vaccination policy.

1. Introduction

From the past to the present, infectious diseases have threatened humans all over the world [1–5]. One of the effective ways to prevent diseases is voluntary (preemptive) vaccination. However, the behavior has a social dilemma structure. Basically, people can prevent diseases by getting vaccinated but hesitate to do so because they will bear the cost. Nevertheless, if people do not get vaccinated, they may be infected, which is worse than paying the vaccination cost. Here, once "herd immunity" [6] is achieved in communities, not getting vaccinated is more attractive to people because the risk to be infected is greatly reduced in such a situation. Thus, people want other people to get vaccinated but do not want to be vaccinated themselves. People want a free ride on other people's cooperative behavior. Because of this dilemma, it is difficult to spread the voluntary vaccination.

Many studies have been done to investigate situations which promote voluntary vaccination. First, game theoretic models with epidemic dynamics have been used to explain the individual vaccination in well-mixed populations [7–10], random networks [11,12], or scale-free networks [13]. The game theoretic analysis commonly assumes that the strategy for vaccination is static. However, in reality, it can be changed over time as the epidemic spreads. Then, evolutionary game theoretic models combined with epidemiological dynamics classified as "evolutionary vaccination games" have been developed [14–18]. Since real human interactions can be described by networked populations, some studies focused on

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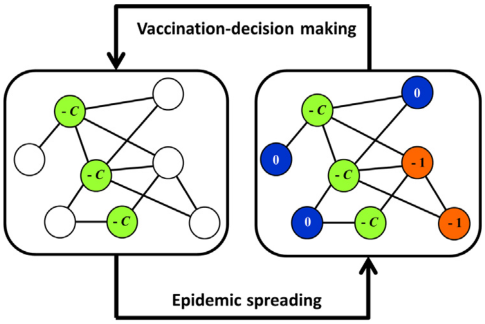

Fig. 1. Our model consists of two stages: decision-making and epidemic spreading. In the decision-making stage, each individual makes a decision whether to get vaccinated or not. If an individual chooses to get vaccinated, his payoff is $-C$ because of the vaccine cost but results in the perfect immunity against the flu-like disease. After that, the epidemic spreading takes place according to SIR dynamics. If an individual gets infected, his payoff is -1. If an individual can avoid the disease, his payoff is 0 because he does not need to pay any cost. The vaccinated individuals never get infected. Since we suppose a seasonal influenza-like disease, it disappears at the end of the season. At the beginning of the next season, individuals have to make a decision again based on the last year's outcome, and then the next epidemic starts. These two stages are repeated every year.

evolutionary vaccination games using heterogeneous networks [19–22]. Fu et al. and Cardillo et al. revealed that vaccination is effective despite the high cost in heterogeneous networks compared to homogeneous networks, because once hub nodes are vaccinated, the behavior immediately spreads to the whole population [19,20]. Cardillo et al. , however, have shown that if the vaccine is imperfect, homogeneous networks conversely outperform heterogeneous networks [20]. Recently, Han and Sun considered a dynamic model of the evolutionary vaccination game in which the relationship among individuals is dynamically changed over time [23]. Another study focuses on multiple networks in the evolutionary vaccination game [24].

In those networked models, when imitation of the strategy is conducted, only the payoff information of one particular neighbor is obvious. If people use broader information, what happens to the dynamics? Based on this motivation, several studies used various types of information such as, social status information [25], memory [26], memory and conformism [27], and other-regarding tendencies [28]. Fukuda et al. investigated the effect of social status information in which each individual can use the information of the average payoff of its neighbors instead of the payoff of one randomly selected neighbor [25]. The idea comes from the study of the evolution of cooperation which shows that cooperation is promoted using a social average payoff [29]. Fukuda et al. showed that the effectiveness of the social status depends on both network structures and the cost of vaccination. In a similar study, Zhang incorporated the effect of the neighbors' payoffs, called "other-regarding tendency", and showed that the tendency influences the vaccination coverage differently depending on the vaccination cost [28]. Moreover, Han and Sun considered the situation that hub players can greatly influence others on networks [27]. They showed that not following such hubs contributes to the large vaccination coverage.

Those studies use the payoff of others as the broader information. In reality, people sometimes follow their neighbors' decisions irrespective of the payoff. In other words, people may compare the number of vaccinated neighbors with non-vaccinated neighbors and then imitate the majority of them. In this paper, we propose a new model in which the effect of such "social impact" [30] is incorporated on networks. Wu and Zhang have recently developed a similar model called "peer pressure" where an individual is influenced by the number of neighbors who have a different strategy [31]. Our computer simulation results show that, in heterogeneous networks, when the cost of vaccination is low, influential social impact increases the vaccination coverage. On the other hand, the impact reduces the coverage if the cost is high. Moreover, since the vaccination coverage of homogeneous networks is lower than that of heterogeneous networks as we will show, following the social impact in homogeneous networks may pose a great threat to society.

2. Model

We developed a model in which an epidemic spreading and individual decision-making take place alternately. Before the epidemic spreads, individuals make a decision whether to get vaccinated or not based on their vaccination strategy. The decision is affected by the payoff of others or the social impact, which is controlled by the probability α. Then, epidemic spreading takes place based on the standard susceptible–infectious–recovered (SIR) model. Here, we assume seasonal influenza as the target disease. To realize them, we consider two stages: decision-making stage and epidemic spreading stage (Fig. 1). The detail of each dynamic is the following.

2.1. Decision-making stage

Each individual makes a decision whether to take vaccination or not. We assume that the vaccine gives the perfect immunity to vaccinated individuals. Once an individual decides to get vaccinated, his payoff is $-C$ as the vaccination cost ($0 \leq C \leq 1$). The cost may include the monetary cost and the side effects. When an individual chooses not to get vaccinated, there are two situations. If the individual is infected, the payoff is -1 because getting infected is the worst case. In contrast,

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