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Preferential imitation can invalidate targeted subsidy policies on seasonal-influenza diseases

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ABSTRACT

In this paper, under the complex network framework, we study a seasonal influenza-like disease model by incorporating the interplay between subsidy policies and human behavioral responses. In the model a small proportion of individuals are freely vaccinated according to either the targeted or random subsidy policy in advance, while the remaining individuals choose to vaccinate (or not) based on voluntary principle and update their vaccination decision via an imitation rule. Our findings show that the targeted subsidy policy is only advantageous when individuals prefer to imitate the subsidized individuals' strategy. Otherwise, the effectiveness of the targeted policy is worse than that of the random subsidy policy, since individuals preferentially select non-subsidized individuals as their potential imitation objects. More importantly, under the targeted subsidy policy, preferential imitation causes a non-trivial phenomenon: that the final epidemic size increases rather decreases with the proportion of subsidized individuals. We further define social cost as the sum of the costs of vaccination and infection, and study the impact of each subsidy policy on the social cost. Our result shows that there exist some optimal intermediate regions leading to the minimal social cost.

1. Introduction

Vaccination is the most effective response to large-scale epidemic outbreaks, because it both limits the extent of the outbreak and reduces morbidity and mortality [1,2]. However, on one hand, electing to take vaccination brings certain side effects or inconveniences; on the other hand, vaccines not only directly protect those who are vaccinated but also indirectly protect their neighbors, and resulting in the so-called effect of "herd-immunity". This scenario naturally leads to the problem of "free-riding" commonly observed in public goods studies [3]. By incorporating evolutionary game theory into traditional epidemiological models, many researchers have demonstrated that a voluntary vaccination strategy without incentives may be unable to eradicate a vaccine-preventable disease [4–10]. One possible way of solving the social dilemma with respect to vaccination is to offer some incentive programs, e.g., subsidy and insurance policies [11]. Yet, an important fact cannot

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be ignored: human attitudes to vaccination may accordingly chang when some incentive programs are offered. In this case, the effectiveness of subsidy polices should be re-evaluated.

Since many diseases are often propagated by the physical contacts between infected individuals and susceptible individuals, which can be viewed as the spreading of epidemics in complex networks. In the past decades, network-based epidemiological models have attracted myriad attention and many significant results have been achieved [12–21]. To control epidemic spread in complex networks, many well-studied immunization strategies have been proposed, such as targeted immunization [22–24] and acquaintance immunization [25]. Compared to a random immunization strategy [26], these two immunization strategies have been proven to be more efficient in controlling the spreading of epidemics in complex networks. However, the results are obtained based on two implicit assumptions: (1) there are enough public resources to immunize many individuals; (2) the behavioral responses of the remaining individuals are not considered; which is inconsistent with empirical observations. In reality, government agencies can only provide limited resource to immunize a small proportion of population. The remaining population decides whether or not to take vaccination may based on a voluntary principle – and subject to an associated vaccination cost. In this case, the vaccination decision of the remaining people is dependent on the risk of infection, prevalence of infection, the cost of vaccination, public opinion and so on [27–30]. In particular, their attitudes to vaccination can be influenced by the proportion of subsidized individuals as well as which kinds of individuals are subsidized. For example, Wells et al. have demonstrated that immunization in hub nodes can decrease the vaccination coverage in nodes with small degree [11], which was also partially confirmed by Cornforth et al. [31]. Therefore, we need to reconsider whether the classical targeted subsidy policy (i.e., individuals with the highest degrees are freely immunized) is still better than the random case [11,32], or whether novel targeted subsidy policies are required.

When facing the outbreak of an epidemic, it is hard or even impossible for individuals to act with perfect information to assess their chances of becoming infected, they are likely to adopt new strategies by imitating others who appear to have adopted more successful strategies [9]. Meanwhile, imitation behavior is a form of social learning that leads to the development of traditions and ultimately to cultures. It enables transfer of information among individuals and to future generations without the need for genetic inheritance. Imitation behaviors exist in many contexts, ranging from animal training to international politics [33]. Therefore, the imitation (learning) rule was incorporated in many vaccination decision-making models to depict the vaccination behaviors of individuals, the findings suggest that the imitation rule can yield results different from those based on the self-interested principle [2,9,34].

In this paper, a vaccination decision model with a preferential imitation mechanism based on game theory is established to investigate the interplay of the subsidy policy, the voluntary vaccination decision and the spreading dynamics in networks. We then compare the effects of the targeted subsidy policy with the random policy on the vaccination and epidemic dynamics. We find that, for seasonal influenza-like diseases, the preferential selection mechanism plays a vital role in whether the targeted subsidy policy generates ideal results. We show that the effectiveness of the targeted policy can be generated when those non-subsidized individuals prefer to select the subsidized individuals as imitation targets. Otherwise, the control effect of the targeted policy is even worse than that of the random policy if non-subsidized individuals randomly or preferentially select other non-subsidized nodes as their imitation objects. More importantly, we find that, for the targeted policy, increasing the subsidy proportion may increase rather than reduce the final epidemic size when non-subsidized individuals are preferentially selected. This is because a small subsidy proportion may greatly reduce the vaccination willingness of the non-subsidized individuals. In addition, by defining the social cost as the sum of the costs of vaccination and infection, we find that the social cost non-monotonically depends on the subsidized proportion p for both subsidy policies.

In Section 2, we describe our model of epidemic spreading on complex networks by integrating game theory. In Section 3, we present our main results concerning the effects of the two subsidy policies on the vaccination coverage, the final epidemic size and the social cost. In Section 4, we present conclusion and discussions.

2. Model

Taking into account seasonal influenza-like diseases and the limited effectiveness of vaccines (vaccinated individuals only have perfect immunity from the seasonal influenza in the following epidemic season) [4,34,35], we model the interplay between vaccination dynamics and the epidemic spreading dynamics as an iterative two-stage process: the first stage is the vaccination decision stage, which is implemented before each epidemic season; the second stage is the epidemic season stage, where non-vaccinated individuals may be infected by diseases described by the standard susceptible–infected–removed (SIR) model. The detailed descriptions of the model are composed of the following steps:

Step 1: Generate a standard configuration model [36] with degree distribution $P(k) \sim k^{-3}$. The size of the network studied is $N = 10000$, the minimal and maximal degrees are $k_{min} = 3$ and $k_{max} = \sqrt{N} = 100$, respectively[1]. We also run the model on an email network (see Fig. 8).

Step 2: A fraction p of individuals is chosen to implement the subsidy policy. For the targeted subsidy policy (labeled TAR), at first, all nodes are ranked according to their degree centrality, then a proportion p of individuals with the

[1] Here, we notice that the heterogeneity of networks plays a crucial role in the final results. The change of heterogeneity indeed increases the dimension of complexity of human behavior in vaccination campaign. For simplicity, we mainly focus on standard scale-free network model.