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A dynamic vaccination strategy to suppress the recurrent epidemic outbreaks

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ABSTRACT

Efficient vaccination strategy is crucial for controlling recurrent epidemic spreading on networks. In this paper, based on the analysis of real epidemic data and simulations, it's found that the risk indicator of recurrent epidemic outbreaks could be determined by the ratio of the epidemic infection rate of the year to the average infected density of the former year. According to the risk indicator, the dynamic vaccination probability of each year can be designed to suppress the epidemic outbreaks. Our simulation results show that the dynamic vaccination strategy could effectively decrease the maximal and average infected density, and meanwhile increase the time intervals of epidemic outbreaks and individuals attacked by epidemic. In addition, our results indicate that to depress the influenza outbreaks, it is not necessary to keep the vaccination probability high every year; and adjusting the vaccination probability at right time could decrease the outbreak risks with lower costs. Our findings may present a theoretical guidance for the government and the public to control the recurrent epidemic outbreaks.

1. Introduction

A challenging problem in epidemiology is how to understand epidemic spreading dynamics [1–6] and design informing prevention strategies so that the outbreaks of epidemics could be suppressed or reduced effectively. This problem has got great attention in statistical physics and many other disciplines [2,7,8]. According to the percolation theory, the simplest strategy to suppress the outbreaks is to immunize individuals uniformly or randomly, which the implementation do not require preparation or information at all [9,10]. However, it was revealed that random immunization is inefficient for heterogeneous networks. And then, many more effective immunization strategies were developed, ranging from global strategies such as targeted immunization based on node degree [10] or betweeness centrality [11], to local strategies such as acquaintance immunization [12] and (bias) random-walk immunization [13,14], and to some others in between [15]. Later, the graph partitioning [16] and optimization of the susceptible size [17] became the new improvements. Besides the degree heterogeneity, community structure has a major influence on disease immunity [18,19]. Recently, based on the message-passing approach, an optimal set of nodes for immunization [20] was found, and the immunization was mapped onto the optimal percolation problem [21]. Inspired by the idea of explosive percolation, an "explosive immunization" method has been proposed [22]. In contrast to the above approaches, recent research increasingly explored the pivotal implications of individual behavior in populations, such as reducing the risk of infection by adaptive rewiring the links incident to infected individuals [23], information-driven vaccination [24], and the dynamical interplay between awareness and epidemic spreading [25]. These strategies can theoretically prevent the prevalence of an epidemic and thus bring us a huge hope of controlling an epidemic.

All the above studies are focused on the prevention of a single outbreak of epidemic. However, in realistic situations, the empirical data shows that some epidemics are recurrent, i.e., it will outbreak from time to time [26–29], such as SARS (Severe Acute Respiratory Syndrome), H1N1 (Swine Influenza), H5H1 (Avian Influenza), Ebola, and MERS (Middle East Respiratory Syndrome) etc. If these diseases do not confer immunity, individuals would be infected over and over again. Therefore, an effective dynamic vaccination strategy to suppress the outbreak of recurrent epidemic is called for. As we all know, a large vaccine coverage can greatly reduce the risk of epidemic outbreak, but it increases the health-

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care costs and the financial burden of the public health authorities greatly. In fact, the outbreak of recurrent epidemic is not always seasonal and there is even no outbreak in some years [26]. Therefore, we are wondering whether the immune coverage can be adjusted according to the outbreak risk every year so that the recurrent epidemic outbreak can be suppressed to the greatest extent at lowest cost. More precisely, is't possible to improve the immune coverage before a higher risk of epidemic outbreak and decrease the immune probability in lower risk case?

To achieve the above goal, in this paper, we firstly introduce a network model of SIRS to reproduce the spreading pattern of recurrent epidemic. Then, we try to find out the risk indicator of epidemic outbreak based on our proposed model. Lastly, according to the risk indicator, a dynamic vaccination probability is designed year by year to suppress the epidemic outbreak. Our simulation results show that the dynamic vaccination strategy is much more effective than the other vaccination ones. Particularly, the dynamic vaccination could decrease the maximal and average infected density but increase the time intervals of epidemic outbreak and individuals attacked by epidemic at very low cost. These findings are very useful for public health authorities to optimize vaccination and drug delivery plans.

The paper is organized as follows. In Section 2 the network model and the epidemic spreading model are introduced. Next in Section 3 the risk indicator of epidemic outbreak based on our proposed model are determined. Based on the risk indicator, a strategy with dynamic immune probability is proposed in Section 4. Then, a theoretical analysis based on Markov dynamics is presented to explain the numerical results in Section 5. Finally the main conclusions and discussion are addressed in Section 6.

2. The recurrent epidemic model

In this section, the recurrent epidemic spreading model on complex network is produced. In a network, each node represents an individual, and the epidemic spreads among them along the connections. Here, we take the uncorrelated configuration model (UCM) as an example. By following Ref. [30], we construct the UCM network with size $N = 1000$ and the degree distribution $p(k) \sim k^3$, where the degree k is limited in the range $k \in (4, \sqrt{N})$.

In the study of epidemic spreading, scientists design many infectious disease model [2], and the most widely used models are SIS model (Susceptible - Infected - Susceptible) and SIR model (Susceptible - Infected - Recovered). These two models in the process of transmission system may eventually reach a steady state [31], namely the number of susceptible, infected and refractory individuals are (almost) constant. But in reality it's well known that some diseases exist for a long time and fluctuate occasionally, such as the Influenza. Influenza virus persists in the population and causes outbreaks of disease once in a while. Therefore, the two classic epidemic models are not suitable for the transmission of recurrent epidemic.

Recently, Zheng et al. [26] have designed a model of recurrent epidemic spreading, which takes into account environmental factors and seasonal variations in the infected rate. In particular, as is shown in Fig. 1, susceptible individuals may be infected with the probability β by the infected neighbors, and it may also be infected by the virus in the surrounding environment at a certain probability p_0. Then the infected individuals are recovered to refractory state with the probability μ. And then the refractory individuals will change into susceptible state with the probability of δ. In our simulation, μ and δ are fixed at 0.20 and 0.02. In this model, when $p_0 = 0.00$, the infected density will decay to zero, and when $p_0 \approx 0.01$ the infected density can be sustained and can reproduce the recurrent behaviors of non-periodic epidemic patterns, thus p_0 is set as 0.01. For the infection rate β, it will change every 52 time step (corresponding to one year, and one time step represents one week), since the strain of influenza virus change every year. The value of the infection rate in each year is randomly chosen from the truncated Gaussian distribution with average $\langle\beta\rangle$ and standard deviation σ. In this paper, $\langle\beta\rangle = 0.1,\ \sigma = 0.1$ are fixed and only positive β is reserved.

3. The risk indicator of the recurrent epidemic outbreak

The ultimate aim of the study on epidemic spreading is to control it. To avoid infecting from some epidemics, such as influenza, vaccination is advised every year. It's believed that to prevent the influenza outbreaks the best way is to keep the immune probability as high as possible. However, high probability of immunization will cost greatly and the risk of influenza outbreaks may not be high every year. Then a question is addressed: Is it possible to regulate the immune probability of each year with the outbreak risk? That is to say, when the outbreak risk is high, the immune probability is large, and vice versa. If this strategy is effective, outbreak could be controlled at a lower cost. To realize this idea, first of all, the risk indicator of recurrent epidemic outbreak should be identified.

In our former work [26], it has been found that the recurrent outbreaks of epidemic depend not only on the infection rate but also on the density of susceptible individuals. Each year, the World Health Organization (WHO) [32] provides formal recommendation for the composition of influenza vaccines based on the information provided by the WHO Global Influenza Surveillance and Response System, which makes the estimation of the basic reproduction number R_0 [33] possible to some extent. It may reflect the infected rate in an indirect way. But in reality, it's hard to count the number (or density) of the susceptible individuals. We believe there must be something else that could indicate the high density of susceptible individuals. For this purpose, we turn to study the time series of the weekly consultation rates of influenza-like illness (per 1000 consultations) from 1999 to 2013 in Hong Kong for the General Out-Patient Clinics (GOPC) and the General Practitioners (GP) [34], which are shown in Fig. 2. From the figures we noticed an interesting phenomenon: in a period before most outbreaks (not all) the average consultation rate is lower than the average one, which are marked by the light blue ellipses. The consultation rate could be regarded as the density of infected individuals, and the low infected density in a period means less individuals to be in refractory state in the next period, as a result more individuals are in the susceptible state, i.e., low infected density in a period will make large susceptible density in the next period. This may be the reason for the above phenomenon.

In Ref. [26], we have presented a model to simulate non-periodic outbreaks of recurrent epidemics, and it has been proved that the model could well simulate the influenza outbreak process. Inspired by this model, we are wondering whether the phenomenon that lower infected density before outbreak could also be detected in this model. Fig. 3(a) and (b) show the evolution of infection rate β and the infected density ρ_I in our model, respectively. The horizontal black line represents the average infection rate $\langle\beta\rangle$. Arrows 1, 3 and 4 indicate the typical outbreaks and the light blue ellipses indicate the infected density before the outbreaks. The simulation time series can well reflect the non-periodic and persistently outbreak features (see Fig. 2). What's more, it's also found that in a period before most outbreaks (not all) the infection density is relatively lower (marked by light blue ellipses), which is similar to the phenomenon in the real data (see Fig. 2). However, both the simulations and real data indicate that not all the lower infection density will indicate the emergence of the outbreaks in the coming period. Thus, lower infected density in the