

DOCTORAL THESIS

A computational study on vaccination decision making for infectious disease control

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A Computational Study on Vaccination Decision Making for Infectious Disease Control

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Principal Supervisor: Professor LIU Jiming

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Abstract

Vaccination is one of the most effective methods of preventing infectious diseases by immunizing a critical portion of host population (i.e., over a herd immunity threshold). The challenge for public health authorities lies in how to achieve a timely and adequate level of vaccination coverage needed for preventing outbreaks, especially against an emerging infectious disease, e.g., 2009 influenza A (H1N1). This challenge is twofold. On the one hand, the constrained capacity of development, manufacturing, and logistics lead to a limited vaccine supply. In this case, vaccination programs may cover only a part of the host population. On the other hand, individuals make their own decisions on whether or not to be vaccinated, which will collectively affect the actual level of vaccine uptake. Facing with these issues, in this thesis, we focus on the problem of how to evaluate and improve the effectiveness of vaccination programs in controlling infectious diseases. To address such a problem, we develop a computational approach to characterizing vaccination decision making at two levels: (1) population-level vaccine allocation decision making; (2) individual-level voluntary vaccination decision making.

At the population level, due to the limited vaccine supply, public health authorities need to determine how to allocate a given number of vaccine doses to certain individuals/subpopulations that can most effectively benefit the whole population. Regarding such a problem, we investigate the impact of host population heterogeneities on the dynamics of disease spread. Then, we determine how to target subpopulations for vaccine allocation. In doing so, we develop a modified compartmental model that incorporates individuals' age-specific

heterogeneities in terms of population-dependent susceptibility and infectivity. Moreover, due to the lack of the accurate and reliable descriptions about individuals' contact relationships responsible for disease transmissions, we utilize a computational method to infer individuals' cross-age contact patterns (i.e., the contact frequency and structure) from the social-demographical data of the population. Next, based on the proposed epidemic model, we develop a prioritization method that estimates the relative priority of each subpopulation by computing the effects of vaccinating individuals of certain ages for reducing disease transmissions. By doing so, we can address the problem of vaccine allocation by targeting certain subpopulations so as to most effectively to prevent disease spread in the whole population.

At the individual level, in the context of voluntary vaccination, individuals' decisions have an impact on the actual vaccination coverage, which will crucially affect the effectiveness of disease control. In order to understand the impact of voluntary vaccination, we develop decision models to characterize and evaluate individuals' vaccination decision making during an epidemic. In doing so, we identify several key factors that affect vaccination decisions from the empirical studies on public acceptance of vaccines: they are (1) the risk and benefit of vaccination, (2) the impact of social influence, and (3) individuals' subjective perceptions. For the risk and benefit of vaccination, we utilize a payoff-based approach to representing vaccination decision making as individuals' self-initiated cost minimization. For the impact of social influence, we further explore the Social Impact Theory (SIT) to describe vaccination decision making with respect to individuals' social interactions. Finally, in order to evaluate individuals' subjective perceptions, we extend the Dempster-Shafer Theory (DST) to model the spread of awareness during an epidemic and characterize vaccination decision making corresponding to individuals' perceptions about disease severity and vaccine safety. By doing so, we can investigate the impact of individuals' vaccination decisions on the resulting coverage of a voluntary vaccination program and, thereafter, assess

the effectiveness of disease control.

In order to demonstrate the performance of the proposed prioritization method for population-level vaccine allocation and decision models for individual-level voluntary vaccination, we carry out a series of simulation-based experiments to investigate the spread of an influenza-like disease and the implementation of vaccination programs. We describe the real-world scenario of the 2009 Hong Kong H1N1 influenza epidemic and determine the relative priorities for age-specific vaccine allocation. In addition, we examine the impact of social influence and the spread of awareness by representing individuals' interaction relationships with reference to real-world social networks. In this case, we evaluate individuals' voluntary vaccination corresponding to several impact factors, including the relative costs of vaccination and disease infection, the strength of social influence, and the spread of awareness about negative events of disease and vaccine.

In summary, this thesis emphasizes the development of computational methods to investigate the population-level vaccine allocation and the individual-level voluntary vaccination. The work as demonstrated in this thesis can provide public health authorities with further insights into the improvement of vaccination programs to more effectively control infectious diseases.

Keywords: Infectious Disease Control, Vaccine Allocation, Vaccination Decision Making

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