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Modelling the Logistics Response to a General Infectious Disease

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Abstract: As an infectious disease has serious consequences and demands medical resources suddenly, an emergency management plan which can reduce the number of deaths should be studied. However, the papers in this area are still few and no paper proposes a model which can be adapted to general infectious diseases. This paper proposes a model which links the disease progression, the related medical intervention actions and the logistics deployment altogether to support the decision making process in case of the logistics response to an infectious disease from a strategic level. The number of the patients in different disease stages and the required medical resources for each period can be estimated by our model. The factors which have a great impact on the number of deaths can also be evaluated by this model. Numerical results take the H5N1 as an example to assess the potential contribution of our model.

Keywords: Medical systems, Decision making, Modelling, Nonlinear models, Emergency logistics

1. INTRODUCTION

The infectious disease, such as H5N1 (avian influenza), can pose a great threat to the public health and lead to severe consequences. In order to reduce the threat and the consequences, an effective response plan is needed. Though several studies have been made about the response to the infectious disease, some crucial questions are still open and, in particular, those concerning the response to the infectious disease from the logistics part, preciously, the decisions on inventory allocation.

Papers about the infectious disease prevention and control can be classified into three groups: the prevention of certain diseases, the medical intervention policies and the research methods. Many papers specialize in just a certain disease, such as smallpox, HIV (human immunodeficiency virus) and influenza. Jamrog et al. (2007), Edward et al. (2002) and Kress (2005) compared the different control and response policies of the smallpox. The HIV prevention policies have been studied by Kahn and Auvert (2006), Bertolli et al. (2003), Nakchbandi et al. (1998), Sanders et al. (2005) and Kaplan et al. (2002). Due to its frequent occurrences, influenza was another hot topic (Tan et al., 2013; Zhou and Guo, 2012). Some papers specialize in different prevention and control policies. Wallinga et al. (2005) and Zaric et al. (2000) compared the different medical intervention policies with the aim of maximizing the number of immune individuals. The economic cost of the medical interventions has been studied by Meltzer (2008) and Lee (2008). Some papers specialize in the research methods. Different types of models are available in this field: Markov process models (Jamrog et al., 2007), simulation (Hupert et al., 2002), compartmental model (Allen and Burgin, 2000) and network model (Porco et al., 2004). However, there are relatively few papers studying the medical resource allocation for the response to an infectious disease. An example is Brandeau (2004).

Based on these previous works, it can be found that papers studying the logistics response to the infectious disease are far from being enough. Moreover, to the best of our knowledge, until now, no paper has proposed a logistics response model which can be adapted to the response to a general infectious disease other than a certain infectious disease. These gaps motivate us to propose a logistics response model for general infectious diseases, which connects the disease progression, the medical intervention methods and the logistics deployment together. By using this model, crisis managers can estimate the number of patients in different stages for each period and then optimize the resources for the best response. Therefore, this model will help the crisis managers to organize an efficient logistic response to a general infectious disease from a strategic level.

The remainder of this paper is organized as follows. Section 2 describes the background of the problem. The logistics response model and the related mathematical formulation are presented and discussed in section 3. Section 4 reports numerical experiments to assess the potential contributions of our model. Conclusion and future research directions are provided in Section 5.

2. PROBLEM DESCRIPTION

In order to give the reader a general view of the situation that we intend to address, this section describes the general situation of an infectious disease and the decisions concerning the logistics problems of medical interventions.

2.1 General Situation of an Infectious Disease

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The progression of a general infectious disease can be divided into three stages according to the infectiousness, namely, latent (L), infectious (A) and isolated (I) stages. The patients in L stage are non-infectious. The A stage patients can infect the susceptible (S) individuals. When the A stage patients develop to the I stage, they are not infectious anymore because the infectiousness first increases and then decreases with the time, such as smallpox patients; or the patients are symptomatic and will be isolated, such as H5N1 patients. Some infected patients eventually recover even though they do not get the medical help because they can produce antibody themselves. The infected patients who cannot produce antibody themselves will pass through these stages and die (D) if untreated. Susceptible people can be infected by two ways. First, they may inhale or contact with the virus or bacterial dust and become ill. Second, they may get infected by contacting with infectious patients. In epidemiology, the basic reproduction number, defined as the number of susceptible individuals that can be infected by each patient during the infectious periods, is always used to describe the infection rate of the disease.

Generally, two medical intervention methods are available: vaccination (V) and antiviral drugs or antibiotics (D). The susceptible individuals can become immune by vaccination. But the vaccination can also cause fatalities because of the side effect. Usually, the antiviral drug and the antibiotics are used to treat patients infected by the virus and the bacteria respectively. If the S stage and I stage individuals who get the medical help cannot become immune or recover, they are still likely to be infected and infect others respectively.

2.2 Logistics Decisions

The logistics deployment of drugs and vaccines is managed both at national and local levels. At the national level, national strategic stocks are supposed to supply the necessary amount of drugs to the Antiviral drug Distributions Centres or Antibiotics Distributions Centres (ADC), as well as the vaccines used by the hospitals. Usually, vaccines are only available in the hospital that is appointed or related. In most cases, the national stock is available round the clock every day and the available medical resources can be delivered to the local ADCs in time. We will therefore focus on the local level decisions in the infected region. At the local level, a complex network delivering both services (diagnosis or injection) and products (antiviral drugs or antibiotics and vaccines) needs to be deployed as soon as possible.

According to the WHO (World Health Organization), the antiviral drugs or antibiotics and the vaccines should be stocked in advance to response to the occurrence of an infectious disease. However, it is difficult to prepare the stockpiles of vaccines in advance for two reasons: first, there are too many types of viruses and so it is hard to stock the vaccines for every infectious disease; second, the production and stock costs of the vaccines are too high. Though it is difficult, it is not impossible. To deal with different epidemics, different drugs should be dispensed in time. But, the logistic capacity is always limited. All these problems make a big challenge for the logistics organization to meet the high demand of the scare medical resources after the sudden occurrence of an infectious disease.

The model proposed in this paper is not to address all the logistics questions during the response to epidemic, but to assess the potential and the generality of our approach. According to the requirement of WHO mentioned in the previous paragraph, we limited the scope of our model to the following logistic-related decisions, especially decisions on inventory allocation. First, how should the antiviral drugs or antibiotics be prescribed? Since the infected patients in the different stages ask for the same antiviral drugs or antibiotics, who should get the most part of the antiviral drugs or antibiotics? Second, should certain kinds of vaccines be stocked in advance? If yes, how many hospitals should be involved to inject the vaccines? Third, how does the change of the dispensing capacity of ADCs affect the number of deaths? Is the national stockpile always enough to support the local ADCs? Fourth, the different infectious diseases have different basic reproduction numbers, how will different basic reproduction numbers affect the number of deaths and the use of medical resources?

3. THE GENERAL INFECTIOUS DISEASE MODEL AND THE MATHEMATICAL FORMULATION

This section first discusses our general infectious disease model and then the mathematical formulation aiming at minimizing the number of deaths caused by a general infectious disease under limited medical resources.

3.1 The General Infectious Disease Model

The proposed model (Figure 1) takes account of the different disease stages and the potential medical intervention methods. The notations used in Figure 1 are defined in Table 1. This model consists of a set of nodes (the disease stages under different medical treatment situations) and oriented arcs (possible transitions between the stages). The individuals are divided into 10 stages according to the different disease stages and different medical treatment statuses which they are in. These stages are denoted by $\mathrm{m} = \{S, L, A, I, S^V, L^D, A^D, I^D, R, D\}$. The normal letter stands for the disease stages: susceptible (S), latent (L), infectious (A), isolated (I), immune or recover (R) and dead (D). The superscript indicates the medical treatment that the patients receive (if applicable): receiving antiviral drugs or antibiotics (D) and receiving the vaccines (V). If there is no superscript, that means the patients do not receive the medical help. Transition between the different stages is based on different disease stages, different medical treatment statuses and the results of different medical interventions. The model assumes that logistics decisions (delivery of medical resources) are made at the beginning of periods. The individuals who are in the current stage at the beginning period t may evolve to the following stage at the beginning of period t+1 (at the end of period t) according to the medical decisions taken at the beginning of period t. Hence, our