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Modeling the logistics response to a bioterrorist anthrax attack

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ABSTRACT

As a bioterrorist anthrax attack has serious consequences, an emergency management plan that can reduce the number of casualties should be studied. However, the papers studying this area are still few. This paper proposes a model which links the disease progression, the related medical intervention actions and the logistics deployment together to help crisis managers to extract crucial insights on emergency logistics management from a strategic level standpoint. This model is a multi-period one with the consideration of the period when the patients transfer into the different disease stages, the period when the medical intervention begins and the change of the recovery rate because of the time lag between the two aforementioned periods. Our model can support the decision making process in case of a real anthrax attack and evaluate the important factors, which can have a great impact on the number of casualties.

1. Introduction

Bacillus anthracis, the bacteria causing Anthrax, is classified by the Centers for Disease Control and Prevention (Atlanta, U.S.A.) as one of the most likely agents to be used for biological attack. It may spread across a large area, and needs a great deal of planning for the protection of the people's health. Already known as an efficient biological warfare weapon, anthrax spores become part of terrorists' arsenals in the aftermath of the September 11, 2001 terrorist's attacks, when concentrated anthrax spores were delivered by mailing postal letters containing the spores. As a result, 22 were infected and five died. Since then, the use of weaponized anthrax spores has become a major threat for the civil population (Berman & Gavious, 2007). An effective emergency management plan can obviously reduce the number of casualties and the serious consequences of an anthrax attack. Even though several studies have been made about the response to the anthrax attack from different perspectives, some crucial questions are still unanswered. Questions concerning the suitable dispensing capacity of the antibiotics distribution centers (ADC), the utilization of sensors to improve the anthrax detection ability, and the choice of patients who should get the medical help first need, among others, need to be addressed in the design of the most effective post-attack response.

This paper proposes an original modeling approach inspired by Markov decision process. It combines the progress of the anthrax disease, the medical response, and the logistic deployment choices. In particular, the approach allows us to capture dynamically the impact of different medical responses on the infected population. Dynamics are important because the time elapsed since the patient is infected till the moment he/she receives medical treatment has a major impact on the recovery rate, the survival rate and, therefore, on the number of deaths. Crisis managers need to assess how their decisions, in particular these concerning the deployment and operation of an antibiotics' distribution network, will determine the access of infected people to medical treatment. Our model allows to estimate the number of individuals infected in different periods and the number of patients in each stage of the disease for each period. Based on this information, crisis managers can optimize the resources' deployment for the best response. The model is flexible and can adapt to specific situations and various resource deployment scenarios. The remainder of this paper is organized as follows: Section 2 briefly reviews the related literature. Section 3 describes the background of the problem. The anthrax response model and the mathematical formulation are presented and discussed in Section 4. Section 5 reports numerical experiments assessing the potential of our approach. Conclusion and future research directions are provided in Section 6.

2. Literature review

This part contains a brief review of the related papers studying the response to the anthrax attack in terms of methodologies and research content. Doubtless, the three-paper series (Craft, Wein, & Wilkins, 2005; Wein & Craft, 2005; Wein, Craft, & Kaplan, 2003) constitutes one of the first and most important contributions to the field. The first paper in this series (Wein et al., 2003)

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considered an airborne anthrax attack and proposed a mathematical model to compare five priority policies to determine who should get the medical help first according to two criteria based on patients' ages and their symptomatic/asymptomatic state. This model incorporated an atmospheric dispersion model, an age-dependent dose-infected model, a disease progression model, and an intervention policy model. Even though the paper takes into account the limitation of the medical treatment capacity, it does not address logistics questions such as the number and the size of the antibiotic distribution centers to deploy. The second paper in this series (Craft et al., 2005) simplified the model proposed by Wein et al. (2003) and used the number of deaths as a key parameter to analyze the response to the anthrax bioterrorist attack. The third paper (Wein & Craft, 2005) used the model proposed in the second paper to discuss four different public health intervention methods, such as the pre-exposure prophylaxis and post-exposure prophylaxis.

The literature contains other important contributions to different aspects of the study of anthrax. Brookmeyer, Johnson, and Barry (2005) studied anthrax's progression focusing on the incubation period. Based on the competing risk formulations, several models were developed to number the spore clearance and germination. These models could be used to predict the length of time for which each individual will remain in each of the different disease stages. Bravata et al. (2006) evaluated the costs, cost-effectiveness and lives saved by four alternative strategies (cost–effectiveness analysis). They concluded that the local dispensing capacity is the most important factor to restrain the mortality rate in an anthrax bioterrorist attack. Hu and Zhao (2001) used system dynamics to analyze the different emergency response modes to an anthrax attack. Jamrog, Shatz, and Smith (2007) used Markov chains to model the response to the anthrax attack and, again, concluded that the antibiotic distribution capacity is a key factor to reduce causalities. Zaric et al. (2008) used the compartmental approach, which aims at reducing the population diversity to a few key characteristics relevant to the disease, to study the progress of an epidemic and the intervention policies. The model developed by Zaric et al. (2008) was used to evaluate the costs and benefits of various strategies (cost–benefit analysis). Houck and Herrmann (2011) and Herrmann (2013) extended the model in (Zaric et al., 2008) to estimate the number of casualties in the situation where authorities pre-position medications (MedKits) in individual households to be used in case of need. They run several sensibility analysis and concluded that, in all the cases, prepositioned medications strongly reduce the mortality rate. Our model adopts a similar compartmental approach, based on a network of states and a set of probabilities defining the transitions between them. However, we use linear programming to optimize medical and logistic decisions. For example, the model decides how to allocate the available treatments among the different compartments provided a given inventory replenishment policy. Also, although we do not explicitly consider the use of pre-positioned MedKits, the comportments modeling them can be added in a straightforward manner.

Whitworth (2006) used a discrete-event simulation approach to design and evaluate the response processes to an anthrax attack. The author's simulation model enabled evaluation of candidate points of dispensing, alternative dispensing processes, staffing plans, and traffic-management strategies. But no criterion is optimized in this paper. To the best of our knowledge, this is the only paper using discrete-event simulation to study the response to anthrax attacks.

There are other interesting papers devoted to planning the response to bioterrorist attacks, although they consider other biological agents. Bozzette et al. (2003) investigated different vaccination policies for the response to the outbreak of smallpox. Berman, Gavious, and Menezes (2012) studied a potential smallpox attack in an airport terminal, and proposed a resource allocation model to minimize the number of deaths. Murali, Ordóñez, and Dessouky (2012) studied the response to a large-scale bioterrorist attack and proposed a facility location problem to tackle it. Liu and Liang (2013) proposed a dynamic optimization model for allocation of medical resources during the outbreak of an epidemic.

To the best of our knowledge, we did not find any paper studying the response to anthrax attack using heuristics to generate a good response policy because, first, anthrax is a non-communicable disease which can be presented by a linear model and so exact method can be used to find the optimal solution; second, the response to anthrax attack should consider lot of factors (ADC, hospitals, inventory stocks, drug deliveries, etc.) and so it is a big problem, which make the use of heuristics not be a good choice. But, some researchers adopted heuristics when they study communicable disease because of the non-linear nature of disease propagation. For example, Ren, Ordóñez, and Wu (2013) presented a multi-city resource allocation model to dispense a limited amount of vaccine to minimize the total number of fatalities due to a smallpox outbreak. Heuristics has been used to solve this non-linear problem.

In short, papers studying the emergency response to an anthrax attack are few. Though these papers made great contributions to this field, some gaps need to be filled. First, most of these models failed to combine some factors which can impact their accuracy estimating the number of casualties, such as the different moments in which patients transfer into the different disease's stages, the decrease of the drugs' efficiency as treatment is delayed, and the limitation of the logistics capacity. Second, not all the papers studying the response to the anthrax were based on real cases and consider a given emergency management plan. Third, most of the papers tried to compare the different response modes but did not pay attention to what the crisis manager can do under the current situations. In other words, the question of how to optimize the utilization of the resources based on the current situation, such as which is the best way to distribute the antibiotics effectively, did not get enough attention. These drawbacks make it difficult to put into practice the existing emergency management plans. According to Altay and Green (2006), the randomness of disasters requires a dynamic and effective solution, thus making the topic very suitable for operational research. Therefore, we propose a multi-period mathematical model, which takes into consideration the disease's dynamic and the impact of the decisions managers on the planning of a response after an anthrax attack.

3. Basis of the model

In order to give the reader a general view of the situation that we intend to address, this section describes firstly the progression of the anthrax and the transitions between the different stages of the disease; secondly it presents the three phases of a response to an anonymous bioterrorist attack with anthrax; finally it describes the decisions concerning the logistics of medical help delivery.

3.1. Anthrax's progression and its stages

The progression of anthrax is divided into three stages, namely, incubation (i), prodromal (p), and fulminant (u) stages, as illustrated in Fig. 1. During stage i, people infected by anthrax spores have no symptoms, but patients in stage p show a spectrum of non-specific symptoms, such as fever, chill, cough and vomiting. In stage u the patients develop the symptoms abruptly, with high fever, dyspnoea, diaphoresis and shocks, or more specific and severe symptoms. We assume that all the infected individuals