Simulating the Response of a Rural Acute Health-care Delivery System to a Bioterrorist Attack

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Objectives: This paper demonstrates the applicability of discrete event simulation to planning the response of a rural acute health-care delivery system to a bioterrorist attack. Simulation results are used to develop observations and recommendations for planning for bioterrorism events in rural settings. Method: The analysis employed two discrete event simulation models, one representing the spread of disease following an attack with a contagious agent (pneumonic plague) and the other representing the care that victims would receive from the acute health-care delivery system and the resultant stress the attack would put on the health-care infrastructure. Results: In the scenario simulated in this study, early detection of the attack and subsequent aggressive response by the public health system were projected to reduce the total number of victims in this rural setting from 82 to 27 and to reduce deaths from 43 to 7 when compared with a less timely and less effective response. Early detection also created more favourable lead-times for acquiring necessary equipment that would be in short supply. For example, in all cases simulated, additional ventilators were needed 5 days after the attack. This allowed 2 days for acquiring ventilators with the most optimistic time to detect, but no time under a less optimistic assumption. In all cases, the need for ICU beds greatly exceeded the available supply. However, this shortfall could be alleviated if some medical/surgical (M/S) beds could be temporarily staffed and equipped for near-ICU use, as the demand for M/S beds peaked later in the crisis than for ICU beds. Conclusion: Rural acute health-care delivery systems can minimize mortality and cope with the surge in demand associated with a bioterrorist attack through high public health preparedness, plans for efficient access to needed resources, and creative use of scarce resources. The study illustrates the value of mathematical modelling as an aid in planning for such an attack. Key words: bioterrorism, discrete event simulation, rural hospitals, surge capacity, pneumonic plague.

INTRODUCTION

The US General Accounting Office has noted that ‘there is little or no excess capacity in the health care system for accepting and treating mass casualty patients’ [1]. Concern that community medical infrastructures are inadequate to respond to a biological or chemical attack has led the Institute of Medicine to recommend the development and use of computer-related tools to improve community medical response capabilities [2]. This paper presents emerging results from an ongoing research programme to develop and apply such tools toward a better understanding of the resources and strategies needed for effective community response to a bioterrorist attack.

The tools include two discrete event simulation models, one representing the spread of disease following the attack and the other representing the care that victims would receive from the acute health-care delivery system and the resultant stress the attack puts on the health-care infrastructure. We applied the tools to investigate the response to a hypothetical pneumonic plague attack occurring in a metropolitan area and spreading to the rural community that was the focus of our analysis. Experiments were conducted varying a series of actions that could be implemented by the public health and the acute health-care delivery systems to both reduce demand and increase available resources. The results show some of the effects of preparedness and early intervention in terms of fewer victims needing treatment and better outcomes, and also the timeline on which intervention decisions, both by public health officials and acute health-care delivery system managers, would have to be made to be effective.

Previous modelling efforts have addressed aspects of the community response to surge requirements associated with a bioterrorist attack. Among these are modelling of (a) strategies for smallpox vaccination [3, 4] or antibiotic
prophylaxis [5] following an attack, (b) alternative public health responses to a pneumonic plague attack on a major city [6], (c) strategies for dealing with an anthrax attack [7], and (d) design and staffing of a large-scale smallpox vaccination clinic [8] or an antibiotic distribution centre [9]. Our research recognizes and builds on these efforts, but with a focus on the response of the patient care delivery network in a rural environment rather than the public health focus and urban setting of most earlier efforts.

DESCRIPTION OF THE USED AGENT

Pneumonic plague has been placed near the top of the CDC’s list of ‘Critical Biological Agents’ [10], and is designated a CDC Category A agent [11]. Victims who inhale the infectious aerosol released from a weapon develop primary pneumonic plague, the most severe form of plague. Victims will develop symptoms in 1–6 days, but most often symptoms appear in 2–4 days [10, 12].

The disease is transmitted via droplets from a coughing victim. Assessments of transmissibility vary widely. At one extreme are statements such as, ‘Russian experts believe plague is so transmissible that almost everyone exposed to a contagious person will catch pneumonic plague’ [13]. At the other extreme are arguments that transmission will occur only through carelessness by uninfected individuals [14]. This latter position is supported by a quantitative estimate based on historical data that suggests there would be an average of 0.4 secondary cases from each primary case [15]. The former transmission rates could result in a rapid overwhelming of the medical system, while the latter would result in very few cases. Our analysis takes a middle ground that produces a case mix that stresses the medical system while still leaving some opportunity for consequence management.

Aggressive use of antibiotics has been recommended for anyone with a fever or cough in the presumed area of exposure, and for post-exposure prophylaxis for asymptomatic persons who have had close contact with victims [10]. Prophylaxis results in milder cases of the disease in those who contract it [16], and is predicted to lessen mortality [10]. Mortality rates are extremely high for patients who do not receive antibiotics in the first 18 hours after developing symptoms [10, 12]. While no specific rates are identified in the literature, our analysis team, after consulting with physicians, assumed the following: if not recognized and not treated, mortality is 98%; if recognized and treated routinely, mortality is 60%; if the patient was given an early intervention administration of antibiotics before becoming symptomatic, mortality is 10%.

MATERIALS AND METHODS

The scenario

The setting for the analysis was Bastrop County, Texas, a rural county near Austin (see Fig. 1). Bastrop County is served by Smithville Regional Hospital (SRH) [17], a community hospital located in the city of Smithville. The hospital has 27 medical/surgical (M/S) beds, a 6-bed emergency room, a 4-bed intensive care unit (ICU) and 2 surgical suites. The medical/surgical capacity can be expanded by 10 beds within 24 hours of a crisis. SRH refers patients to several hospitals in Austin. Bastrop County also has clinics and private physician offices located in the cities of Bastrop and Smithville that refer patients to the hospital in Smithville.

The scenario posited a terrorist attack in Austin involving the release of pneumonic plague at an event attended by residents of Bastrop County, who infected others in the county upon their return. As infected patients began to present for care, the community recognized that an attack had occurred.

Optimistic and pessimistic versions of the scenario were developed to reflect different levels of assumed preparedness. A timeline of major events in the scenario appears in Fig. 2. Recognition that an attack had occurred was an important element of the scenario and was based on assumptions of when the attack was recognized in Austin, the timeliness and effectiveness of communications between Austin public health and Bastrop County officials, the arrival of the first victims, and the timeliness of the first confirmation of a pneumonic plague diagnosis. With the optimistic scenario timeline, recognition of the crisis occurred 3 days after release of the agent; 5 days were assumed with the pessimistic timeline. At the time of recognition, the medical system modified its treatment protocol to one that recognized the existence of plague cases in the population and presumptively treated suspected cases. At the same time, the public health response began. Among the public health activities were public service announcements that resulted in a reduction in contacts among members of the public, thus reducing transmission of the disease. The public health system simultaneously began to mobilize for distribution of surgical masks, which caused a decline in transmission of the disease, and prophylactic antibiotics. With the optimistic timeline, mask and antibiotic distribution began 4 days after the attack and eventually reached 80% of the population. With the pessimistic timeline, distribution began 8 days after the attack and reached only 50% of the population.

The models

The Healthcare Complex Model (HCM) is a discrete event simulation that represents health-care delivery at
the patient-episode level throughout a network of medical facilities [18]. The model represents the arrival of patients to each hospital or clinic and employs a set of clinical protocols to describe the diagnosis and treatment of each patient’s underlying condition. The triage and clinical decision processes that might competitively assign a scarce resource to a particular patient are not explicitly modelled. However, the results of those decisions (in terms of the flow of patients among diagnostic and treatment services and resultant patient outcomes and consumption of resources) are subsumed in the probabilities applied to each patient within the appropriate clinical protocol. The model tracks resource utilization and patient outcomes, and can be used to identify bottlenecks in the care delivery process. Over the past 9 years, the HCM has been applied in numerous studies to help guide

![Map of Bastrop County, Texas with event locations and timelines.](image)

**Fig. 1.** Pneumonic plague scenario in Bastrop County, Texas.

**Fig. 2.** Scenario timeline (optimistic version).
re-engineering of the health-care delivery process. Recent enhancements have configured the model to support planning for the medical response to a bioterrorist event [19, 20].

A total of 10 HCM clinical protocols describe the activities and resources involved in diagnosing and treating pneumonic plague victims and potentially exposed and concerned persons, termed ‘worried well’ (see Fig. 3). These protocols represent treatment of plague victims in three different age groups and under three different circumstances: prior to attack recognition and post recognition, the latter with and without the effects of prophylactic intervention. In addition, a single protocol represents the process used to treat the worried well.

Incidence timelines for plague victims were generated with the use of a casualty prediction model that we developed for this purpose. The model is a discrete event simulation that represents contacts and disease transmission between infected and previously unexposed individuals. Its output is a time history of individuals who are infected and subsequently seek care. While the model was developed to generate inputs to the HCM for this study, it has a generic structure allowing it to be used for other scenarios and other diseases.

Outputs from the casualty prediction model appear in Fig. 4, which displays the average number of daily arrivals of plague victims to Bastrop County medical facilities for both the optimistic and pessimistic variants of the scenario. On average, the 4 initial cases led to a total of nearly 27 infected patients in the optimistic case and nearly 82 in the pessimistic case. The daily averages shown in the figure were used to generate the random arrival stream of plague victims in the HCM.

Material

Eleven HCM cases were run to investigate the capability

<table>
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<tr>
<th>Protocol</th>
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<th>Paediatric</th>
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<th>Geriatric</th>
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of the Bastrop County public health and acute health-care delivery systems to cope with the hypothesized crisis. Thirty replications of each case were run and the results were averaged to achieve statistical stability. Results included mortality, bed utilization, ventilator utilization, emergency department (ED) requirements and provider time requirements. The next section summarizes and interprets the most significant of these results, which involve mortality, bed utilization and the demand for ventilators.

RESULTS

Mortality

The mortality of plague victims in the scenario depended on whether the optimistic or pessimistic timeline was achieved and whether or not early intervention (in the form of prophylaxis) was implemented. Figure 5 displays the cumulative expected number of deaths associated with each of the four cases representing (a) the optimistic timeline with early intervention, (b) the optimistic timeline without early intervention, (c) the pessimistic timeline with early intervention, and (d) the pessimistic timeline without early intervention. Death rates were higher in the pessimistic cases than the optimistic ones, and reached their peak later in the crisis. Rates were reduced when early intervention was pursued. For either the optimistic cases or the pessimistic ones, death rates were identical with and without early intervention during the first several days of the crisis and began to diverge only when prophylactic antibiotics had begun to cause a reduction in deaths (day 8 in the optimistic cases and day 11 in the pessimistic cases). By the end of the crisis, early intervention was projected to save nearly seven lives in the optimistic situation, reducing the mortality rate from 52% to 27% of those infected. It was projected to save 12 lives in the pessimistic situation, reducing the mortality rate from 52% to 38% of a larger number of infected individuals than with the optimistic timeline. If early recognition, aggressive response and early intervention could all be achieved, more than 35 lives were projected to be saved in comparison with the least favourable case.

Bed utilization

Figure 6 displays the requirement (i.e. unconstrained demand) for and availability of staffed beds in the optimistic situation with no early intervention. (Early intervention resulted in a similar pattern but lower demand for both ICU and M/S beds.) Bed availability was based on current capacity, ability to increase capacity in a crisis, historical occupancy rates, and estimates of the number and timing of occupied beds that could be made available (through early release of patients, deferral of elective surgeries, etc.) after recognition of a crisis. While there were adequate M/S beds to meet the demand, the requirement for ICU beds exceeded the supply 4 days after the attack.

However, this bottleneck could be alleviated if some M/S beds could be temporarily converted for near-ICU

![Fig. 5. Cumulative mortality.](image-url)
use during the crisis. Figure 7 illustrates the requirement for and actual use of both bed types in the optimistic situation with no early intervention under the assumption that such temporary conversion would be possible. As ICU beds began to fill, M/S bed use increased, first to accommodate ICU patients, and subsequently to accommodate these same patients as their condition improved and they required only M/S beds. This approach would be possible, of course, only if the needed equipment and staff to serve ICU patients were available in adequate supply for these patients while they occupied M/S beds.

Figure 8 is similar to Figure 7; it depicts the requirement for and use of beds in the pessimistic situation with early intervention. In this case, the demand for each bed type was greater than in either of the optimistic cases, and exceeded the supply of beds even if M/S beds could substitute for ICU beds. (Demand was even higher in the pessimistic situation without early intervention.) The figure illustrates the resulting unmet demand for both bed types. Here the demand for ICU and M/S beds was exceeded approximately 12 days after the attack, requiring transfer of some patients to another hospital. As before, the excess demand was mitigated somewhat by the phased requirements for the two bed types: the demand for M/S beds grew as the need for ICU beds began to decline, providing some capability to minimize the transfer of patients.

**Ventilator utilization**

The requirement (unconstrained demand) for ventilators as a function of time is illustrated in Figure 9 for each of the four basic cases. The five ventilators currently available in Bastrop County did not quite meet the average peak demand in the optimistic case with early intervention, and significantly more ventilators would be required (from other hospitals, national stockpiles, etc.) for each of the other cases considered. In all cases, the demand for ventilators began to exceed the supply approximately 5 days after release of the agent. This was 2 days after recognition of the crisis under the optimistic timeline, but was the day of recognition using the pessimistic timeline, allowing no lead-time for acquisition. This emphasizes the importance of early recognition and stockpiles of supplies and equipment that are readily available with a short lead-time.

**DISCUSSION**

This analysis has illustrated the stress that might be placed on a rural hospital in the event of a bioterrorist attack with pneumonic plague in a nearby large city. The actual demand for the services of the hospital will depend on a number of factors that are not fully understood. These include, for example, the transmissibility of the disease, its lethality under alternative treatment regimes, and the
extent to which the crisis generates large numbers of worried well presenting for diagnosis and treatment. Sensitivity analysis has allowed us to explore the effects of some of these uncertain factors, and the model and data are now available for efficient further investigation of these and other factors.

Fig. 7. Bed utilization – optimistic timeline, no early intervention.

Fig. 8. Bed utilization – pessimistic timeline, with early intervention.
In spite of such uncertainties, a number of observations can be drawn from the analysis conducted to date. It has illustrated the benefits of early detection of the attack and subsequent aggressive response. Even in a rural setting with a very small number of initially infected victims, such responsiveness can save a significant number of lives and can result in a major reduction in the demand for the scarce resources needed to treat primary and secondary victims.

This response must involve several simultaneous activities. Public health efforts to limit exposure to infected individuals (through distribution of surgical masks and public announcements encouraging the public to limit contacts with others) can help keep the number of casualties to manageable levels. Early intervention in the form of distribution of antibiotics to possibly exposed individuals can lessen the severity of the disease and greatly decrease mortality. Instructions to the public and providers to help limit the number of worried well who present for care can help ensure that emergency rooms are not so overwhelmed that seriously ill patients do not receive timely care. (While such overwhelming of the ED was a minor problem in the cases considered in this analysis, a larger number of victims or worried well might have had a more significant effect.)

The analysis has also illustrated the need for rural communities to plan for efficient access to medical resources that would be in great demand and in short supply in the event of a bioterrorism crisis. These include, for example, ventilators, providers with the appropriate specialties, and antibiotics. (Antibiotics were assumed to be available in this analysis, but their extensive use would probably require that they be acquired quickly from sources outside the affected area.) Early detection creates more favourable lead-times for acquiring these resources by the time they are needed.

Creative use of available resources is also an important aspect of planning for a surge in demand associated with a bioterrorism attack. For example, patterns in the time-phased demand for different types of beds might result in an opportunity for temporary use of some beds for secondary purposes. Special procedures for efficient handling of large numbers of uninfected patients presenting for emergency care (as were assumed to be used in this study) can help reduce bottlenecks for treatment of seriously ill patients.

Now that models and data have been developed for this rural setting, the preliminary analysis documented here could easily be extended to address specific issues of interest to planners in a specific community or for more general planning for rural hospital preparedness. Such analysis could address specific capacity planning issues for SRH or (with minor modification of data) other rural hospitals. Further sensitivity analysis could help develop a better understanding of the impact of uncertain inputs (such as disease transmission rates) or to separate the effects of several actions that were considered in combination in this study (such as time to detection and

![Ventilator requirements](image-url)

*Fig. 9. Ventilator requirements.*
the efficiency of the subsequent public health response. Some effects that were not addressed in this analysis could be included in subsequent analysis. Examples include the impact of limited availability of antibiotics, the potential of increased transmission of the disease to the worried well when they appear for emergency care, the potential decrease in available health-care providers who become infected while treating victims, and the possible increase in morbidity or mortality of victims assigned to M/S beds when ICU beds are not available. But the analysis conducted to date illustrates the potential of model-based analysis for developing an improved understanding of the need for and effectiveness of alternative measures to improve the surge capacity of a rural hospital.

Continuing research is exploiting and expanding the results of this initial effort.

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