A Geographic Simulation Model for the Treatment of Trauma Patients in Disasters

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Abstract

Background: Though the US civilian trauma care system plays a critical role in disaster response, there is currently no systems-based strategy that enables hospital emergency management and local and regional emergency planners to quantify, and potentially prepare for, surges in trauma care demand that accompany mass-casualty disasters.

Objective: A proof-of-concept model that estimates the geographic distributions of patients, trauma center resource usage, and mortality rates for varying disaster sizes, in and around the 25 largest US cities, is presented. The model was designed to be scalable, and its inputs can be modified depending on the planning assumptions of different locales and for different types of mass-casualty events.

Methods: To demonstrate the model's potential application to real-life planning scenarios, sample disaster responses for 25 major US cities were investigated using a hybrid of geographic information systems and dynamic simulation-optimization. In each city, a simulated, fast-onset disaster epicenter, such as might occur with a bombing, was located randomly within one mile of its population center. Patients then were assigned and transported, in simulation, via the new model to Level 1, 2, and 3 trauma centers, in and around each city, over a 48-hour period for disaster scenario sizes of 100, 500, 5000, and 10,000 casualties.

Results: Across all 25 cities, total mean mortality rates ranged from 26.3% in the smallest disaster scenario to 41.9% in the largest. Out-of-hospital mortality rates increased (from 21.3% to 38.5%) while in-hospital mortality rates decreased (from 5.0% to 3.4%) as disaster scenario sizes increased. The mean number of trauma centers involved ranged from 3.0 in the smallest disaster scenario to 63.4 in the largest. Cities that were less geographically isolated with more concentrated trauma centers in their surrounding regions had lower total and out-of-hospital mortality rates. The nine US cities listed as being the most likely targets of terrorist attacks involved, on average, more trauma centers and had lower mortality rates compared with the remaining 16 cities.

Conclusions: The disaster response simulation model discussed here may offer insights to emergency planners and health systems in more realistically planning for mass-casualty events. Longer wait and transport times needed to distribute high numbers of patients to distant trauma centers in fast-onset disasters may create predictable increases in mortality and trauma center resource consumption. The results of the modeled scenarios indicate the need for a systems-based approach to trauma care management during disasters, since the local trauma center network was often too small to provide adequate care for the projected patient surge. Simulation of out-of-hospital resources that might be called upon during disasters, as well as guidance in the appropriate execution of mutual aid agreements and prevention of over-response, could be of value to preparedness planners and emergency response leaders. Study assumptions and limitations are discussed.

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Introduction

The US trauma care system provides coordinated and timely medical care on a daily basis for patients with severe injuries, a significant percentage of whom otherwise would die without specialty care.[1] In addition to this daily function, the trauma system also plays a critical role in responding to mass-casualty disasters.[2-4] This reality has been highlighted in many national catastrophes, including the terrorist attacks (New York USA) of September 11, 2001,[5] and the more recent Boston (Massachusetts USA) Marathon bombings[6] and Philadelphia (Pennsylvania USA) train derailment.[7] Despite a widespread professional acknowledgement of the role of trauma systems in disasters, there is no widely used, systematic strategy to appropriately prepare these systems for the surge in health care demand that accompanies mass-casualty incidents.

This report proposes a quantitative model that ultimately might be used by hospital emergency management and local and regional emergency planners to quickly simulate the acute effects of a fast-onset, single epicenter disaster, such as a terrorist bombing, to the surrounding health system. The model includes outputs for the predicted response by the trauma system, based on known numbers of casualties and the medical resources in and around a specific disaster epicenter. To illustrate the utility of this planning tool, available evidence and data inputs were used to model the disaster preparedness and response capabilities of trauma centers in and around the 25 most highly urbanized US cities, including the nine US cities listed by Congress and the Department of Homeland Security (Washington, DC USA) as being the most likely targets of terrorist attacks.[8,9] The overall goal of this test was to rapidly determine the magnitude of health care assets needed to respond to mass-casualty incidents of varying impacts, and to develop a better idea of the nature of mutual aid agreements and emergency assets that would be needed to adequately respond to a specific number of casualties at a specific disaster epicenter location in each of the 25 study cities.

Importantly, this tool can provide local, state, and federal planners with an estimate of the health care resources needed for specific events relative to the existing capacity of the local trauma system in the impacted area. The model's parameters can be changed to represent the realities of local conditions, such as hospital bed availability, levels of health care staffing, and average transportation times from epicenter to hospitals. Parameters related to the nature of the event itself, for example number of patients, severity of patient injuries, and patient transitions from one disease state to another, can all be customized based on available data and the predictions of local subject matter experts. While the true outcome of any disaster event may never be predicted, the model proposed here establishes an evidence-based starting point for better preparing the nation's trauma systems for their role in disaster response. This ultimately may lead to more timely and efficient allocation of health care assets and reduced morbidity and mortality among casualties. The alternative, executing inefficient disaster response strategies, could result in otherwise preventable death and disability to both the victims and rescuers, as well as to individuals with day-to-day injuries and illnesses who are left with inadequate health care due to medical resources that have been diverted inappropriately in response to a disaster.[10] This scalable proof-of-concept model estimates the geographic distributions of patients, trauma center resource usage, and mortality rates for varying disaster sizes, and its inputs can be modified depending on the planning assumptions of different locales and for different types of mass-casualty events.

Methods

To demonstrate the model's potential application to real-life planning scenarios, sample disaster responses for 25 major US cities were modeled using a hybrid of geographic information systems and dynamic simulation-optimization. In each city, a simulated, fast-onset disaster epicenter, such as might occur with a bombing, was located randomly within one mile of its population center. Patients then were assigned and transported, in simulation, to Level 1, 2, and 3 trauma centers, in and around each city, over a 48-hour period for disaster scenario sizes of 100, 500, 5000, and 10,000 casualties.

Study Sites and Data Sources

The 25 US cities with a population of greater than 2,000,000 people in 2008 served as the study sites: New York (New York), Los Angeles (California), Chicago (Illinois), Philadelphia (Pennsylvania), Dallas (Texas), Miami (Florida), Washington (DC), Houston (Texas), Atlanta (Georgia), Detroit (Michigan), Boston (Massachusetts), San Francisco (California), Las Vegas (Nevada), Phoenix (Arizona), Seattle (Washington), Minneapolis (Minnesota), San Diego (California), St. Louis (Missouri), Baltimore (Maryland), Tampa (Florida), Pittsburgh (Pennsylvania), Denver (Colorado), Cleveland (Ohio), Cincinnati (Ohio), and Portland (Oregon). Nine of these cities listed by Congress and the Department of Homeland Security as being the most likely targets of terrorist attacks were separated out for additional analyses (New York, Washington, Los Angeles, Seattle, Chicago, San Francisco, Houston, Philadelphia, and Boston).[8,9]

Several national databases were used for the analyses: the 2008 American Trauma Society (Falls Church, Virginia USA) Trauma Information and Exchange Program database, the 2008 American Hospital Association (Chicago, Illinois USA) Annual Hospital Survey database, and the 2008 Health Resources and Services Administration (Rockville, Maryland USA) Area Resource File database. Only national databases with information representing the entire US were used to allow for the possibility that medical resources from anywhere in the US potentially could be called upon to assist in disaster response for the 25 study cities.

Only fast-onset disasters were modeled, in which patients presented all-at-once, at a single point in time (for instance, as with a terrorist bombing). These simulated disasters were assigned a geographically random epicenter within a one-mile radius of each study city's population centroid using ArcGIS (ESRI, Inc.; Redlands, California USA). All randomly generated epicenters were restricted to locations on land (no bodies of water qualified to have an epicenter located on them) and not permitted to fall outside of each city's boundaries.

Responses for four increasingly sized disaster scenarios of 100, 500, 5000, and 10,000 casualties were modeled for each of the 25 study cities.[11] A ground travel matrix containing the shortest driving times between the longitude-latitude coordinates of simulated disaster epicenters and the longitude-latitude coordinates of all Level 1, 2, and 3 trauma centers in the US was calculated for each of the 25 study cities.[12] Helicopter evacuations were not incorporated into the models given expert input and prior work[13,14] suggesting that in large, urban, fast-onset disasters, landing zones are limited and only a relatively small number of patients could be evacuated by air from the disaster epicenter in the first 48 hours.

Disaster Response Model

This simulation of the disaster response by trauma care systems, in and around the 25 cities, was operationalized as a computer-based optimization model designed to move patients out from disaster epicenters with the objective of maximizing the number of patients that then reached a trauma center within a specified period of time.

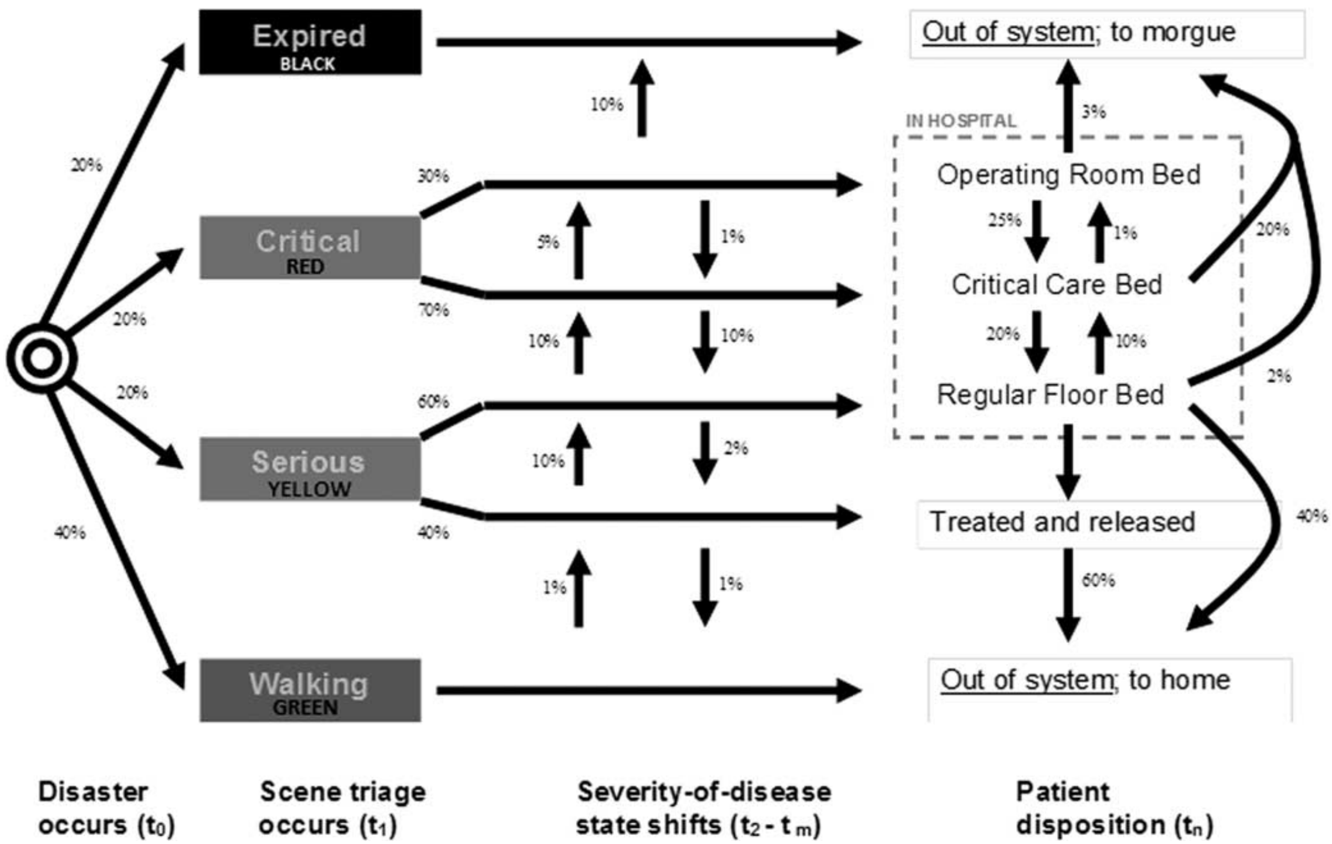

Figure 1. Graphic Model of Disaster Response with Percentages Showing Disaster Occurrence and Initial Patient Triage at Disaster Epicenter, as well as Out-of-hospital and In-hospital Hourly Transitions Thereafter.

This model is illustrated as a disaster response patient flow chart populated with percent transitions per unit time (Figure 1). The model was essentially a mass-balance dynamic simulation model, similar to those used in ecosystem management and forecasting.[15,16] The assumptions listed below were incorporated as rules in a computer-based algorithm that optimized the movement of patients from epicenter to hospital beds and from one severity-of-disease state to another.

All patients were followed for a two-day time horizon, in one-hour increments (48 hours, t_0-t_{48}). All patients were triaged into four severity-of-disease states: expired (black), critical (red), serious (yellow), and walking (green).[17] This model limited patient flows to trauma centers based on available beds: operating room, critical care, regular floor, and treat-and-release beds within each hospital. Patients at the disaster epicenter were transported to the closest available bed of the type they needed.

Except the initial time at each epicenter (t_0), patient percentages in the model were set to experience hourly transitions (from t_1-t_{48}). Patient transitions between severity-of-disease states were accounted for during transport and over the course of hospital care as part of a dynamic triage system. Patients who either began or transitioned to expired (black), or remained or transitioned to walking (green), were considered to be out-of-system (ie, discharged to the morgue or home; Figure 1).

This model objective was completed based on input variables and model constraints that were either fixed by the authors of this study for each disaster epicenter (eg, the number of disaster patients) or dictated by prior reports and members of their team who had direct experience with disasters.[18] These input variables and constraints are described and referenced in an accompanying Appendix (available online only). They include: the initial number of patients at the disaster epicenter separated into severity-of-disease categories; patient evacuation rates from the disaster epicenter to hospitals; patient out-of-hospital severity-of-disease state transition probabilities; reverse-triage of noncritical, non-disaster patients; and hospital bed transition probabilities and patient dispositions. In practice, the values used can be customized based on local data and local predictions to promote the model's future generalizability to other cities and specific disaster situations.

This model required a number of assumptions related to staffing. First, it was assumed that a suitably sized brigade of paramedics, first responders, or other Emergency Medical Services (EMS) personnel were dispatched to each epicenter based on the number of disaster patients. No explicit modeling of paramedics, first responders, or other EMS personnel was conducted as part of the out-of-hospital response because their points of origin (ie, fire stations and the like) were too numerous to account for given the national scope of the model. Hospital-based medical personnel, including emergency physicians and nurses; surgeons, anesthesiologists, and operating room nurses and staff; intensivists and critical care nurses; and general medical staff, such as technicians and others, were assumed to be available (on-duty or able to be activated off-duty) in sufficient numbers to staff beds and care for patients as needed. Moving providers from surrounding hospitals to trauma center hospitals near the disaster epicenters was not included in the model because relocated providers were known to be significantly less efficient in hospitals that are not their own, especially in the first few days after being relocated.[19]

Computer processing times were less than one minute for all models in all 25 cities and all four casualty size scenarios. Response maps for each city were created in ArcGIS to show the trauma centers and volumes of patients involved in eight-hour blocks as the disaster response unfolded. National maps of the outer boundaries of the hospitals required to service disaster patients over the full 48-hour time period were created as minimum bounding convex polygons and then smoothed using a Bezier interpolation algorithm option in ArcGIS.

Results

Total mean mortality rates, in- and out-of-hospital, across all 25 cities, increased by 15.6 percentage points as the size of the disaster scenarios modeled increased, from their lowest point for 100 casualties to their highest for 10,000 casualties. The 100-casualty scenario produced a mortality rate of 26.0% across all 25 cities. The 500-casualty scenario produced a mean mortality rate of 27.4% across all 25 cities, with a low of 26.2% in Philadelphia and a high of 29.8% in Las Vegas. The 5,000-casualty scenario produced a mean mortality rate of 38.0% across all 25 cities, with a low of 33.9% in New York and a high of 40.8% in Seattle. The 10,000-casualty scenario produced a mean mortality rate of 41.9% across all 25 cities, with a low of 39.2% in New York and a high of 43.3% in San Francisco. Mean mortality rates across the nine cities at highest risk of terrorist attacks was lower than that of the remaining 16 cities, except for the 100-casualty disaster scenario (Table 1).

Out-of-hospital Mortality

Mean out-of-hospital mortality rates across all 25 cities increased by 17.2 percentage points as the size of the disaster scenarios modeled increased from 100 to 10,000. Out-of-hospital deaths can be divided into immediate deaths and early deaths. Immediate deaths at the epicenter at t_0 were unalterable by medical care and set (at 20.0%) in the model. Early deaths at the epicenter or en route to a trauma center, in t_1 or later, were related to system capacity to transfer patients from the event scene (evacuation rate) and hospital capacity based on available beds. The 100-casualty scenario produced a mean out-of-hospital mortality rate of 21.3% across all 25 cities, with a low of 21.0% in 18 cities and a high of 22.0% in the remaining seven cities. The 500-casualty scenario produced a mean out-of-hospital mortality rate of 22.8% across all 25 cities, with a low of 21.4% in Boston and Philadelphia and a high of 26.6% in Las Vegas. The 5,000-casualty scenario produced a mean out-of-hospital mortality rate of 33.6% across all 25 cities, with a low of 27.5% in New York and a high of 37.8% in Seattle. The 10,000-casualty scenario produced a mean out-of-hospital mortality rate of 38.5% across all 25 cities, with a low of 33.3% in New York and a high of 41.5% in San Francisco. Mean out-of-hospital mortality rates across the nine cities at highest risk of terrorist attacks was lower than that of the remaining 16 cities, except for the 100-casualty disaster scenario (Table 1).

In-hospital Mortality

Mean in-hospital mortality rates across all 25 cities decreased by 1.6 percentage points as the size of the disaster scenarios modeled increased from 100 to 10,000. The 100-casualty scenario produced an in-hospital mortality rate of 5.0% across all 25 cities. The 500-casualty scenario produced a mean in-hospital mortality rate of 4.6% across all 25 cities, with a low of 3.0% in Las Vegas and a high of 5.2% in Seattle. The 5,000-casualty scenario produced a mean in-hospital mortality rate of 4.5% across all 25 cities, with a low of 2.9% in Phoenix and a high of 6.4% in New York. The 10,000-casualty scenario produced a mean in-hospital mortality rate of 3.4% across all 25 cities, with a low of 1.8% in San Francisco and a high of 5.9% in New York. Mean in-hospital mortality rates across the nine cities at highest risk of terrorist attacks was higher than that of the remaining 16 cities, except for the 100-casualty disaster scenario (Table 1).

Trauma Center Involvement

The mean number of trauma center hospitals involved across all 25 cities increased by 60.4 as the size of the disaster scenarios modeled increased from 100 to 10,000. The 100-casualty scenario involved a mean of 3.0 trauma center hospitals across all 25 cities: 2.0 trauma centers in six cities, 3.0 in thirteen cities, and 4.0 in the remaining cities. The 500-casualty scenario involved a mean of 10.0 trauma centers across all 25 cities, with a low of 6.0 in Tampa and a high of 17.0 in Portland. The 5,000-casualty scenario involved a mean of 45.3 trauma centers across all 25 cities, with a low of 24.0 in Miami and a high of 74.0 in Chicago. The 10,000-casualty scenario involved a mean of 63.4 trauma centers across all 25 cities, with a low of 35.0 in Miami and a high of 99.0 in Chicago (Table 1).

The mean number of trauma center hospitals involved in the nine cities at highest risk for terrorist attacks was higher than in the remaining cities, except for the 500-casualty scenario. The mean number of states in which trauma center hospitals were involved in the disaster response predictably increased as the casualty scenario sizes increased. The mean number of states involved was smaller in all casualty scenario sizes for the nine cities at highest risk of terrorist attacks than the remaining 16 cities (Table 1). The trauma center hospitals and numbers of states involved for each city are shown in the outer boundary trauma center response maps in Figure 2 and Figure 3.

Discussion

The dynamic simulation-optimization models introduced in this report use commonly available administrative health care data to gain insight into the use of existing trauma care systems resources in response to fast-onset disasters. While many different scenarios could be modeled, this report used the example of high-explosive bombs detonated in city-centers across the nation. This example was chosen specifically since the use of high explosives in buildings or public areas is the most frequent terrorism event in the US and a leading producer of large numbers of patients simultaneously in need of trauma centers.[20-22]

The model outcomes showed remarkable variation in mortality rates and trauma center resource utilization across the 25 largest US cities for different disaster sizes. Generally speaking, as the number of casualties grew, out-of-hospital mortality rates increased while in-hospital mortality rates decreased. The authors hypothesize that the seemingly counterintuitive decrease in in-hospital mortality rates in larger disasters is due to the significant increase in the number of patients that expire prior to receiving medical care. These patients are likely to die either at the disaster epicenter or while in transit to the next available trauma center due to longer wait and transport times created as nearby trauma centers reach capacity. Accordingly, cities that were less geographically

Disaster Size				
	100 Casualties	500 Casualties	5,000 Casualties	10,000 Casualties
All Cities Under Study (n = 25)				
Mortality (%)	26.3	27.4	38.0	41.9
Died immediately at epicenter (%)	20.0	20.0	20.0	20.0
Died later at epicenter (%)	1.0	1.0	5.5	10.0
Died in transit (%)	0.3	1.8	8.1	8.5
Died in hospital (%)	5.0	4.6	4.5	3.4
Trauma Center Hospitals Involved	3.0	10.0	45.3	63.4
Operating room beds used	6.0	26.9	137.1	172.8
Critical care beds used	14.6	63.5	332.2	404.6
Floor beds used	14.0	69.0	333.8	366.4
States Involved	1.2	1.7	4.9	6.1
Cities at Highest Risk (n = 9)				
Mortality (%)	26.3	27.0	37.2	41.4
Died immediately at epicenter (%)	20.0	20.0	20.0	20.0
Died later at epicenter (%)	1.0	1.0	5.5	10.0
Died in transit (%)	0.3	1.0	6.7	7.5
Died in hospital (%)	5.0	4.9	5.0	3.9
Trauma Center Hospitals Involved	3.1	9.4	49.8	68.9
Operating room beds used	6.0	29.6	156.8	205.6
Critical care beds used	14.4	67.4	364.2	466.9
Floor beds used	13.9	68.2	352.7	405.9
States Involved	1.1	1.4	4.4	5.4
Remaining Cities (n = 16)				
Mortality (%)	26.3	27.6	38.5	42.2
Died immediately at epicenter (%)	20.0	20.0	20.0	20.0
Died later at epicenter (%)	1.0	1.0	5.5	10.0
Died in transit (%)	0.3	2.2	8.7	9.1
Died in hospital (%)	5.0	4.4	4.2	3.1
Trauma Center Hospitals Involved	2.9	10.3	42.8	60.3
Operating room beds used	6.0	25.4	126.1	154.3
Critical care beds used	14.6	61.3	313.6	375.2
Floor beds used	14.1	69.4	323.2	344.3
States Involved	1.2	1.8	5.2	6.5

Table 1. Outcome and Process Statistics (means) for 48-hour Disaster Response Scenarios
(Note: Increasing casualty sizes, across all 25 cities under study, as well as the cities at highest risk of sudden-onset disaster and remaining cities)

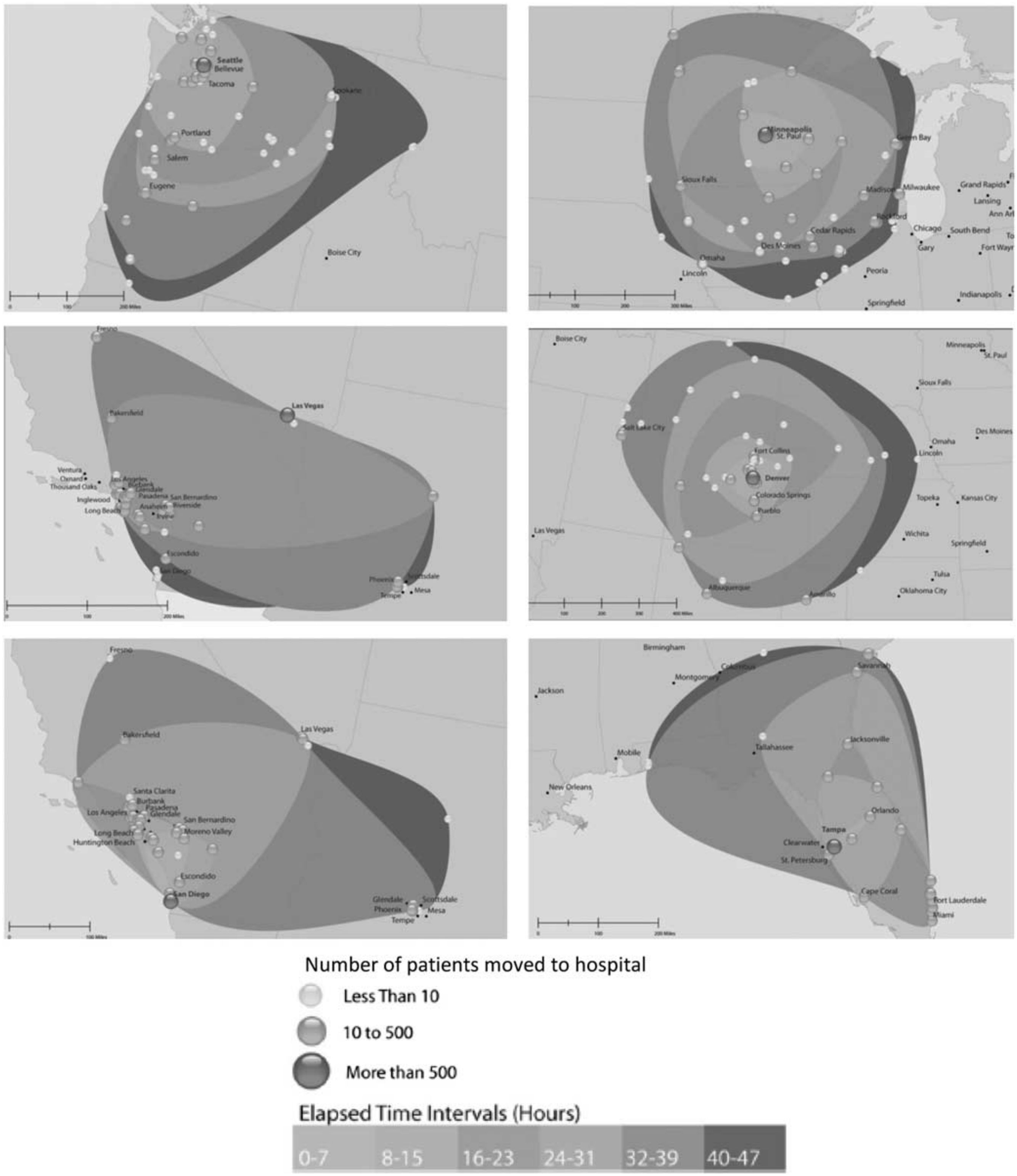

Figure 2. Detailed Outer Boundary Maps of Trauma Center Hospital Catchments Required to Service Disaster Patients in Select Cities under Study within 48-hours for a 10,000 Casualty Disaster Scenario.

isolated and had more geographically concentrated trauma center resources appeared to experience lower out-of-hospital and overall mortality rates. The simulation-optimization models also showed that the nine cities listed as likely terrorist targets had, on average, more trauma center resources available and lower mortality rates in their disaster response scenarios than the remaining 16 cities.

Not surprisingly, the average number of involved trauma centers increased dramatically as the number of casualties

Figure 3. Outer Boundary Maps of Trauma Center Hospital Catchments Required to Service Disaster Patients in all 25 Cities under Study within 48-hours for Disaster Scenarios of Increasing Casualty Sizes.

increased, as did the number of operating room beds, critical care beds, and floor beds. However, these findings are potentially concerning since many of this model's parameters (including transport time, extent of damage to facilities, number of health care response workers available, and availability of beds) were selected based on "best case scenario" inputs and may have overestimated the trauma system's ability to respond in a crisis. According to these optimistic assumptions, disasters with as few as 500 casualties may require the resources of trauma system catchment areas that span many miles and cross multiple state boundaries (Figure 3). As the number of casualties increases, so too do the sizes of the catchment areas necessary to provide sufficient resources. These findings suggest the need to evaluate current emergency and disaster planning to assess whether state- and city-level response capabilities are capable of supporting the trauma care needs required under different planning assumptions, and to what extent inter-facility and interstate agreements may be required to build and sustain a more effective trauma care response. They also draw attention to the need for improved cross-facility and cross-state provider privileging and licensure, as each would be essential to ensuring worker willingness and ability to respond.

The findings also suggest the need for an expanded role of health care assets outside the trauma system in disaster preparedness and emergency response. While the Institute of Medicine (Washington, DC USA) has hailed the US trauma system as a success and has suggested that its regionalized care delivery system should serve as a model for other time-sensitive diseases and hospital care systems,[23] the trauma system alone does not have sufficient infrastructure to absorb the surge of patients that would be seeking care after a sudden-onset disaster, even in the most resource-rich urban areas. Furthermore, trauma systems have largely been designed for the day-to-day care of critically injured patients and relatively little attention has been focused on how best to use the US system of trauma centers during disasters.[2,24,25] Nevertheless, existing prehospital destination protocols, inter-facility transfer agreements, and prospective mutual aid agreements currently used in the US trauma care system could reasonably be expanded to other health care entities in order to create a culture of shared responsibility for critically injured patients.[26] In this spirit, the Department of Health and Human Services (Washington, DC USA) Hospital Preparedness Program has developed health care coalitions that include trauma centers, non-trauma hospitals, and allied health resources to serve as regional, multiagency coordinating groups. Key capabilities of these coalitions, such as rapid reverse triage of hospital inpatients, have been embedded in the models to the extent possible.[10]

The overall utility of this simulation model as a planning tool should not be overshadowed by the specific results of the particular proof-of-concept testing scenario presented here. The model itself is scalable and inputs may be modified depending on the planning assumptions of different geographical areas, trauma and medical systems, and mass-casualty events. Though the findings of this particular proof-of-concept test potentially are useful to hospital emergency management and local and regional emergency planners, if expanded, the real value of this model lies in its ability to be applied practically across all state and local contexts and for a wide variety of potential threats. Such practical application of computer simulation modeling techniques is currently underutilized in disaster planning, and could significantly increase the capability and capacity of the health care system to respond effectively to a wide variety of disasters and public health emergencies.

Limitations

The fundamental disaster model that was employed here (Figure 1) has broad applicability to many disaster response scenarios, and its specific assumptions were designed such that they could be readily altered or updated to suit the needs of specific cities in the future. For the particular test scenario described in this report, the assumption of uniformity in mass-casualty triage is a study limitation deserving further exploration. Although model uniform core criteria for a mass casualty have been proposed by the National EMS Advisory Council (Washington, DC USA),[27] this uniformity has yet to be adopted widely in daily practice. Furthermore, while severely injured patients are likely to arrive at non-trauma center hospitals during disasters,[28-30] the test scenarios included only trauma center assets in their simulation models. Similarly, based on the 48-hour planning assumption for this scenario, estimations of federal support such as National Disaster Medical Service or the military were also omitted. Despite these omissions, however, the underlying models have been built such that estimates of both non-trauma center hospital and federal assets easily can be incorporated in future modeling scenarios. Though the models have been simplified to a certain extent, it also can be argued that they likely benefit from limited complexity[31] while still providing insights and understanding that intuition and human judgment alone may not.[32]

Conclusion

The disaster response simulation model discussed here may offer insights to emergency planners and health systems in more realistically planning for mass-casualty events. Longer wait and transport times needed to distribute high numbers of patients to distant trauma centers in fast-onset disasters may create predictable increases in mortality and trauma center resource consumption. The results of the modeled scenarios indicate the need for a systems-based approach to trauma care management during disasters, since the local trauma center network was often insufficiently large to provide adequate care for the projected patient surge. Simulation of out-of-hospital resources that might be called upon during disasters, as well as guidance in the appropriate execution of mutual aid agreements and prevention of over-response, could be of value to preparedness planners and emergency response leaders. The practical application of these and similar modeling techniques should be utilized more widely in disaster planning.

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Supplementary material

To view supplementary material for this article, please visit http://dx.doi.org/10.1017/S1049023X16000510

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