Optimizing Mass Casualty Triage: Using Discrete Event Simulation to Minimize Time to Resuscitation

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BACKGROUND: Urban areas in the US are increasingly focused on mass casualty incident (MCI) response. We simulated prehospital triage scenarios and hypothesized that using hospital-based blood product inventories for on-scene triage decisions would minimize time to treatment.

STUDY DESIGN: Discrete event simulations modeled MCI casualty injury and patient flow after a simulated blast event in Boston, MA. Casualties were divided into moderate (Injury Severity Score 9 to 15) and severe (Injury Severity Score >15) based on injury patterns. Blood product inventories were collected from all hospitals (n = 6). The primary endpoint was the proportion of casualties managed with 1:1:1 balanced resuscitation in a target timeframe (moderate, 3.5 U red blood cells in 6 hours; severe, 10 U red blood cells in 1 hour). Three triage scenarios were compared, including unimpeded casualty movement to proximate hospitals (Nearest), equal distribution among hospitals (Equal), and blood product inventory–based triage (Supply-Guided).

RESULTS: Simulated MCIs generated a mean ± SD of 302 ± 7 casualties, including 57 ± 2 moderate and 15 ± 2 severe casualties. Nearest triage resulted in significantly fewer overall casualties treated in the target time (55% vs Equal 86% vs Supply-Guided 91%, $p < 0.001$). These differences were principally due to fewer moderate casualties treated, but there was no difference among strategies for severe casualties.

CONCLUSIONS: In this simulation study comparing different triage strategies, including one based on actual blood product inventories, nearest hospital triage was inferior to equal distribution or a Supply-Guided strategy. Disaster response leaders in US urban areas should consider modeling different MCI scenarios and casualty numbers to determine optimal triage strategies for their area given hospital numbers and blood product availability. (J Am Coll Surg 2024;238:41–53. © 2023 by the American College of Surgeons. Published by Wolters Kluwer Health, Inc. All rights reserved.)

Mass casualty incidents (MCIs) often generate more patients than local resources can manage and also disrupt routine healthcare services.[1-5] The incidence of civilian MCIs due to terrorist attacks has increased during the past 2 decades, and mortality from terrorist incidents has more than doubled since 2007.[4,6-9] MCI terror attacks during

Members of the THOR-AABB Workgroup who co-authored this article are listed in the Appendix.

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Abbreviations and Acronyms

AABB	=	Association for the Advancement of Blood and Biotherapies
DES	=	discrete event simulation
IED =	=	improvised explosive devices
ISS =	=	injury severity score
MCI =	=	mass casualty incidents
PLAS	=	plasma
PLT	=	platelets
SALT	=	Sort, Assess, Lifesaving Interventions, Treatment/Transport
THOR	=	Trauma Hemostasis and Oxygenation Research Network

the past decade have ranged in complexity by both multiple sites and modality. The Boston Marathon bombing in 2013, for example, resulted from 2 improvised explosive device (IED) detonations within 100 yards of each other.[10,11] Terror attacks in 2015 in Paris spanned 6 sites with IEDs, mass shootings, and a hostage situation.[12] Blast events have occurred in Israel, Bangkok, Colombo, and Oslo as well.[13,14] Mass transit hubs were targeted in the 2016 Brussels attack as well as in London in 2005.[13,15,16] In parallel, deaths and injuries from mass shootings, an almost uniquely US phenomenon, have also increased significantly.[17-20] Preparing an effective response to civilian MCIs is now a Centers for Medicare & Medicaid Services requirement for healthcare facilities and has become a top priority for hospitals and trauma systems in the US.[21-23]

The timely availability of blood products is crucial for minimizing mortality and morbidity in trauma casualties,[8,9,24,25] yet the demand for blood products generated by MCIs could exceed the local supply.[5] Conversely, increasing blood product inventories at local trauma centers to meet spikes in demand generated by an MCI could increase product waste.[4,26-28] Evaluating local blood product availability and distribution represents a vital aspect of disaster planning, including initial patient distribution, contingencies for blood product resupply, and emergency reallocation of supplies.[3,5,24,29-33] Although disaster response organizations, including local advisory councils, regional task forces, and even federal organizations, may use blood product inventory levels to estimate emergency response readiness,[34] real-time blood product inventory tracking could potentially optimize patient distribution and minimize time to treatment for MCI casualties.

Computer-based simulations allow disaster planners the opportunity to evaluate the optimal blood product resource allocation during MCIs.[7,24,27,28,35] However, previous modeling studies have generally been limited to single trauma center responses without accounting for the critical prehospital or system-level response[29,36] and have not considered in-hospital blood products beyond RBCs. Urban MCIs in the civilian setting often trigger a regional, system-wide response, and in the modern context of damage control resuscitation involve the transfusion of plasma (PLAS) and platelets (PLT) in balance with RBCs as part of a massive transfusion protocol.[9,37,38] To address this knowledge gap, we simulated multiple different MCI locations and modeled strategies for prehospital casualty distribution to appropriate trauma centers with the hypothesis that using hospital-based blood product inventories to guide on-scene patient distribution decisions would minimize time to in-hospital transfusion.

METHODS

Institutional Review Board inquiry at the University of Pennsylvania determined that this study did not qualify as human subjects research; thus, formal IRB approval for this study was not required. In this effort, computer simulations evaluated the system-wide response to an MCI. We developed a Discrete Event Simulation (DES) to model casualty flow from the site of the MCI through their treatment with blood transfusion. This model compared casualty outcomes given different on-scene triage strategies that might be used for a given event in a realistic physical location within the city of Boston, MA, with fixed transport distances and real-world blood product inventories. This specific application is a simulation of a blast event in 4 different potential locations used for mass public gatherings with triage to 6 treating hospitals with hospital names deidentified to maintain anonymity. Triage, in this study, refers to the allocation of casualties to appropriate centers of treatment, not the rapid evaluation and categorization of a casualty's injury status.

In the following sections, we describe the approach taken in this effort, beginning with establishing parameters related to blood supply, MCI casualty populations, and the different steps involved in casualty management. Next, we provide a brief introduction to DES, with its particular use in the MCI model, and detail the different triage strategies investigated here. Finally, we describe the outcomes of interest in this experiment, as well as our methods of analysis.

Emergency scenario definition

Modeling a realistic event depends on accurately representing the event's critical elements and their interactions. For this study, we used the current literature on civilian MCIs as well as expert opinion from among our study group to derive the critical modeling elements, including agents (eg casualties), operations (eg triage, transport, transfusion), and parameters (eg percent of casualties requiring transfusion, travel times, time to transfuse 1 unit of packed RBCs) common in MCIs (**Supplemental Digital Content 1 to 3**, http://links.lww.com/JACS/A311).[21,24,39] We then derived distributions of values for representative parameters, including casualty characteristics and treatment criteria, timing requirements for different stages of triage, transport, and treatment, and hospital blood inventory supplies for use in the model (**Supplemental Digital Content 2**, http://links.lww.com/JACS/A311).

We obtained MCI casualty numbers and injury patterns from the Electronic Mass Casualty Assessment and Planning Scenarios online application.[40] The Electronic Mass Casualty Assessment and Planning Scenarios simulation predicts the number of fatalities and injured survivors along with a list of likely injuries. We chose a single open-air 22.7 kg (50 pound) blast in a crowd with 0.37 m (1.2 foot) spacing between individuals as the optimal event for this study, emulating the blast typical of a suitcase bomb in a dense crowd that might be found in sporting events, parades, and other large public gatherings. We defined severely injured survivors as those with a major torso injury, a major vascular injury, and/or a traumatic amputation (ie those with an injury severity score [ISS] ≥15). A moderately injured survivor was not severely injured but may require blood product transfusion (eg those with an ISS ≥9 and <15).

Each simulated casualty underwent in-field triage, transport to a trauma center, in-hospital triage, assessment and IV access placement, and transfusion if necessary. The time required for a casualty to undergo each stage of care was sampled from unique reported distributions, instead of using constant values for each simulation (**Supplemental Digital Content 2**, http://links.lww.com/JACS/A311).

In 2019, the Trauma Hemostasis and Oxygenation Research Network (THOR)-Association for the Advancement of Blood and Biotherapies (AABB) working party collected blood inventory levels for 98 centers across 6 cities in the US using a survey to quantify RBC (packed RBCs and low-titer O whole blood), PLAS, and PLT units available in the morning and evening of 3 different dates.[5] Boston, MA, 1 of these reporting cities, had 6 trauma centers with a 100% survey response rate for RBC, PLAS, and PLT levels across multiple dates and time points (**Supplemental Digital Content 4**, http://links.lww.com/JACS/A311). The availability of detailed plans and strategies for emergency response in Boston, including the application of these plans to the Boston Marathon bombing, coupled with the robust data of blood inventories in Boston hospitals made the city an ideal selection for simulating a system-wide response. Thus, blood product inventories derived from the THOR-AABB working party study from the 6 Level I trauma centers in Boston were used in the current study in a deidentified fashion.

Model construction and transfusion triage

DES is a methodology for studying subjects as they move through a system.[3] The response to an MCI was translated into a dynamic model of key facilities, services, and providers as deployed in a given response. The simulation includes 3 separate modules: in-field casualty assessment, in-hospital casualty assessment, and casualty treatment.

The initial processing of a casualty at an MCI location included casualty arrival at a centralized triage area, assessment with Sort, Assess, Lifesaving Interventions, Treatment/Transport (SALT) triage by designated officials and assignment to an appropriate treating hospital based on a predefined triage strategy, similar to the process used during the Boston Marathon bombing[33,41] (Fig. 1). The first strategy assigned all patients to the nearest hospital with patient capacity (Nearest), and the second strategy was an equal distribution of patients to all 6 trauma centers (Equal) regardless of the casualty's proximity to any of the 6 hospitals. The third strategy assigned severely injured patients only to 3 trauma centers (hospital A, hospital E, and hospital F) with greater blood product supplies (high inventory; **Supplemental Digital Content 4**, http://links.lww.com/JACS/A311) equally, while moderately injured casualties were assigned to all 6 hospitals equally (Supply-Guided). All these strategies had been observed in recent civilian MCI responses.[4,10,29,36] A detailed description of the simulation model and its modules can be found in the Supplemental Methods (**Supplemental Digital Content 5,** http://links.lww.com/JACS/A311).

Outcomes definition and statistical analyses

We conducted simulation trials to investigate the impact of prehospital triage strategy on system-wide as well as by-hospital outcomes. We simulated a single MCI in 4 different venues that could potentially host large events with a high density of people in Boston (deidentified blast sites Alpha, Bravo, Charlie, and Delta). Travel distances from these locations to hospitals A to F were sourced from the Open Route Source website (https://openrouteservice.org/; Fig. 2; **Supplemental Digital Content 6**, http://links.lww.com/JACS/A311). Trials for each combination of MCI location (n = 4) and triage strategy (n = 3) consisted of 100 simulation runs[29,36] for a total of

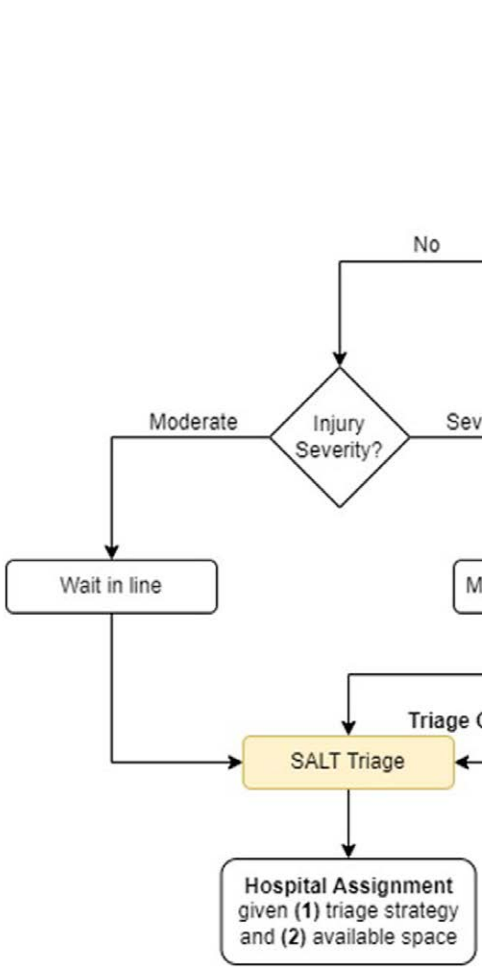

Figure 1. Diagram of in-field casualty processing. Open diamond, control that dictates casualty flow based on characteristics and overall environmental status; open rectangle, action that does not depend on time or provider availability; yellow rectangle, procedure that takes a time and depends on availability of a provider; available space, availability of resources for transport (vehicle) and hospital capacity (patient bed, blood product supplies); triage officer, a designated official responsible for performing pre-hospital Sort, Assess, Lifesaving Interventions, Treatment/Transport (SALT) triage and distributing casualties to treating hospitals.

1,200 simulations. For each simulation run, we sampled casualties from the Electronic Mass Casualty Assessment and Planning Scenarios–generated populations. Hospital blood supply levels were drawn from their normal distributions as determined in the THOR-AABB study for each run.

Treatment, as discussed in this study, refers to blood product transfusion alone, and complete treatment is defined in both quantity of transfused blood products as well as providing said products within a specific window of time. Local transfusion services were expected to be capable of providing moderately injured patients with at least 3.5 U of RBCs per person injured; severely injured patients should have at least 10 U of RBCs person injured available, matching a commonly used definition for massive transfusion.[38,42,43] In these simulations, we evaluated the ideal resuscitation ratio of PLAS and PLT given in equal amounts to RBCs (RBC:PLAS:PLT at a 1:1:1 ratio), as per damage control resuscitation guidelines.[1,25,37] The 2 main outcomes focused on the temporal goals of treating patients in need of blood products, by injury severity: (1) the proportion of severely injured patients treated in the first 60 minutes with 10 U RBC, 10 U PLAS, and 10 U PLT (equivalent of 2 U apheresis PLT) and (2) the proportion of moderately injured patients treated in the first 360 minutes with 3.5 U RBC, 3.5 U PLAS, and 3.5 U PLT (0.7 U apheresis PLT). These values were evaluated across the system of 6 receiving trauma centers and at the individual trauma center level. In addition to casualty-specific outcomes, other outcomes such as minute-by-minute data on blood product supplies as well as blood product depletion were recorded for each trauma center. The secondary outcome for this study is the by-hospital consumption of blood inventory for each of the triage

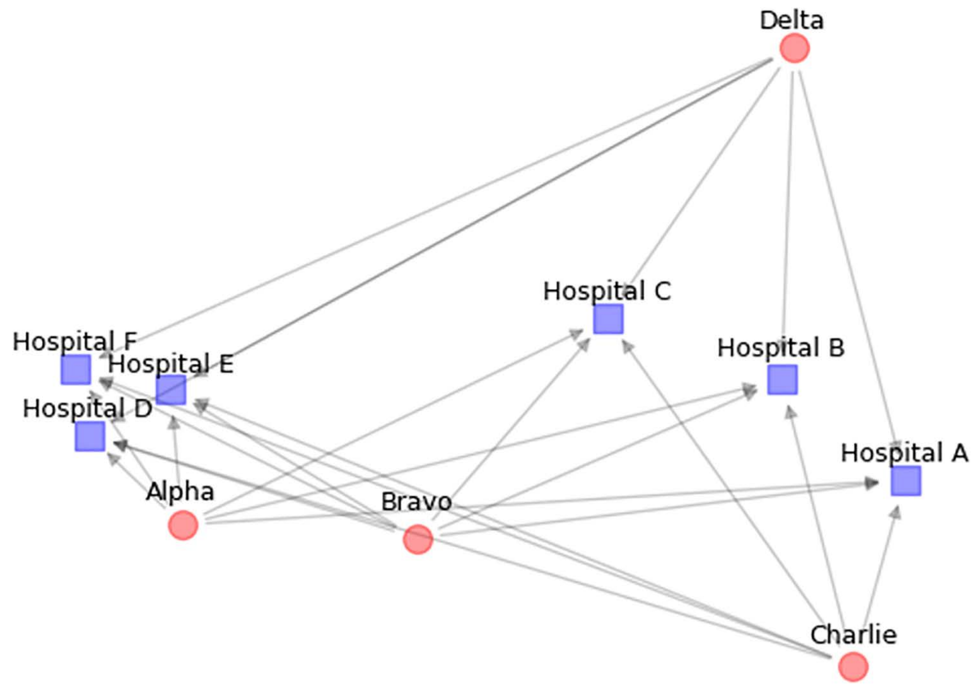

Figure 2. Deidentified distance-adjusted map of Boston mass casualty incident (MCI) blast sites Alpha, Bravo, Charlie, and Delta, and hospitals A to F. Red circle, MCI Location; blue square, hospital; arrow, distance between an MCI location and a specific hospital. All distances sourced from Open Route Service.

strategies, both 1 hour after the MCI (60 minutes) and 6 hours later (360 minutes). This outcome was measured as a percentage of the original supply at a specific hospital.

Triage strategy outcomes were compared using Student's *t*-tests, Holm-Sidak adjusted multiple comparisons, and Mann-Whitney U test for skewed distributions. For all other comparisons across groups, we applied ANOVA. The DES model was developed in Python 3.7.9 using the Simpy module. All statistical analyses were also performed in Python 3.7.9.

RESULTS

The 1,200 simulated MCIs generated a mean ± SD of 302 ± 7 casualties including 57 ± 2 moderately injured casualties, 15 ± 2 severely injured casualties, and 22 ± 4 deaths (Table 1). Applying the Nearest triage resulted in treatment of 55% ± 5% casualties, significantly less in comparison to outcomes given Equal triage (86% ± 4%) or Supply-Guided triage (91% ± 3%; $p < 0.001$ given multiple tests with Holm-Sidak adjustments; Fig. 3). Considering moderately injured casualties, 59% ± 6% were treated within 6 hours given Nearest triage, compared with 96% ± 5% for Equal triage and 99% ± 3% for Supply-Guided triage ($p < 0.001$ given multiple tests with Holm-Sidak adjustments). For severely injured casualties, 42% ± 7% were treated within 1 hour given Nearest triage, which was not significantly different from the outcomes in either Equal triage (48% ± 6%) or Supply-Guided triage (48% ± 7%). A post hoc nonparametric analysis was performed to account for the skewed distribution of outcomes for moderately injured casualties given Equal or Supply-Guided triage, and a Mann-Whitney U test confirmed these differences at the same level of significance. A hospital-level analysis revealed significantly worse outcomes given Nearest triage for hospitals A, B, C, and D, with better outcomes for hospital F ($p < 0.001$; Fig. 4).

Nearest triage resulted in all casualties being treated at the 3 hospitals closest to the MCI location. The closest center received 10 ± 1 severely injured casualties, and the next closest center received the remaining 6 ± 3 severely injured casualties. Within the first hour of treatment, 115 ± 16 U RBC, 111 ± 15 U PLAS, and 111 ± 15 U PLT were used across these 3 hospitals, including the majority of supplies at the closest center (Table 2). Six hours after the MCI event, 361 ± 22 U RBC, 262 ± 18 U PLAS, and 262 ± 18 U PLT were consumed. PLT inventories were nearly exhausted at the closest center for MCIs across all locations, as well as for the next closest center for MCIs at blast sites Charlie and Delta.

Equal triage resulted in each of the 6 centers receiving 12 ± 2 casualties, including 3 ± 1 severely injured casualties within the first hour of response. In that time,

Table 1. Simulation Outcomes by Blast Location and Triage Strategy

Parameter	Blast location Alpha			Blast location Bravo			Blast location Charlie			Blast location Delta		
	Nearest	Equal	Supply-guided	Nearest	Equal	Supply-guided	Nearest	Equal	Supply-guided	Nearest	Equal	Supply-guided
Casualty load (n)												
Total injured	300 ± 14	302 ± 13	301 ± 14	301 ± 13	302 ± 15	303 ± 15	301 ± 14	303 ± 14	301 ± 14	300 ± 13	302 ± 15	302 ± 13
Moderately injured	106 ± 10	107 ± 9	107 ± 10	108 ± 9	108 ± 10	108 ± 11	108 ± 9	108 ± 10	107 ± 10	106 ± 10	108 ± 9	107 ± 9
Severely injured	16 ± 4	15 ± 5	15 ± 4	16 ± 4	16 ± 4	15 ± 4	15 ± 4	15 ± 4	15 ± 4	16 ± 4	15 ± 4	15 ± 4
Time (min)												
Total	61.99 ± 5.28	53.57 ± 4.14	54.82 ± 4.47	64.14 ± 4.55	54.75 ± 5.19	54.78 ± 4.61	63.42 ± 5.05	55.97 ± 4.67	55.38 ± 4.47	63.31 ± 5.26	56.25 ± 4.24	55.31 ± 4.41
In-field triage	35.65 ± 4.61	35.73 ± 4.20	36.92 ± 4.52	37.03 ± 4.37	36.77 ± 5.48	36.89 ± 4.57	36.38 ± 4.89	36.86 ± 4.48	36.22 ± 4.76	36.32 ± 4.12	36.87 ± 4.25	35.85 ± 4.32
Transport	2.82 ± 0.16	5.94 ± 0.39	5.96 ± 0.49	5.22 ± 0.31	5.78 ± 0.31	5.73 ± 0.30	5.62 ± 0.37	9.09 ± 0.57	9.19 ± 0.63	7.23 ± 0.44	9.86 ± 0.61	9.97 ± 0.61
Treatment	6.92 ± 0.82	6.83 ± 0.75	6.87 ± 0.81	6.82 ± 0.70	6.93 ± 0.80	6.84 ± 0.71	6.90 ± 0.84	6.87 ± 0.79	6.80 ± 0.70	6.80 ± 0.77	6.82 ± 0.80	6.82 ± 0.88
Treated (%)												
Severely injured	44 ± 14	51 ± 13	52 ± 14	43 ± 12	52 ± 13	54 ± 13	50 ± 15	46 ± 13	45 ± 13	34 ± 15	44 ± 13	40 ± 13
Moderately injured	73 ± 8	96 ± 9	100 ± 3	66 ± 11	96 ± 10	100 ± 6	61 ± 20	95 ± 9	100 ± 6	35 ± 13	96 ± 9	100 ± 6

Data presented as mean ± SD across all simulations.

Alpha, Bravo, Charlie, Delta, deidentified potential blast sites in Boston, MA; total injured, all casualties generated at a given mass casualty incident; moderately injured, casualties with Injury Severity Score between 9 and 15, severely injured; casualties with an Injury Severity Score greater than 15; min, minutes; n, count.

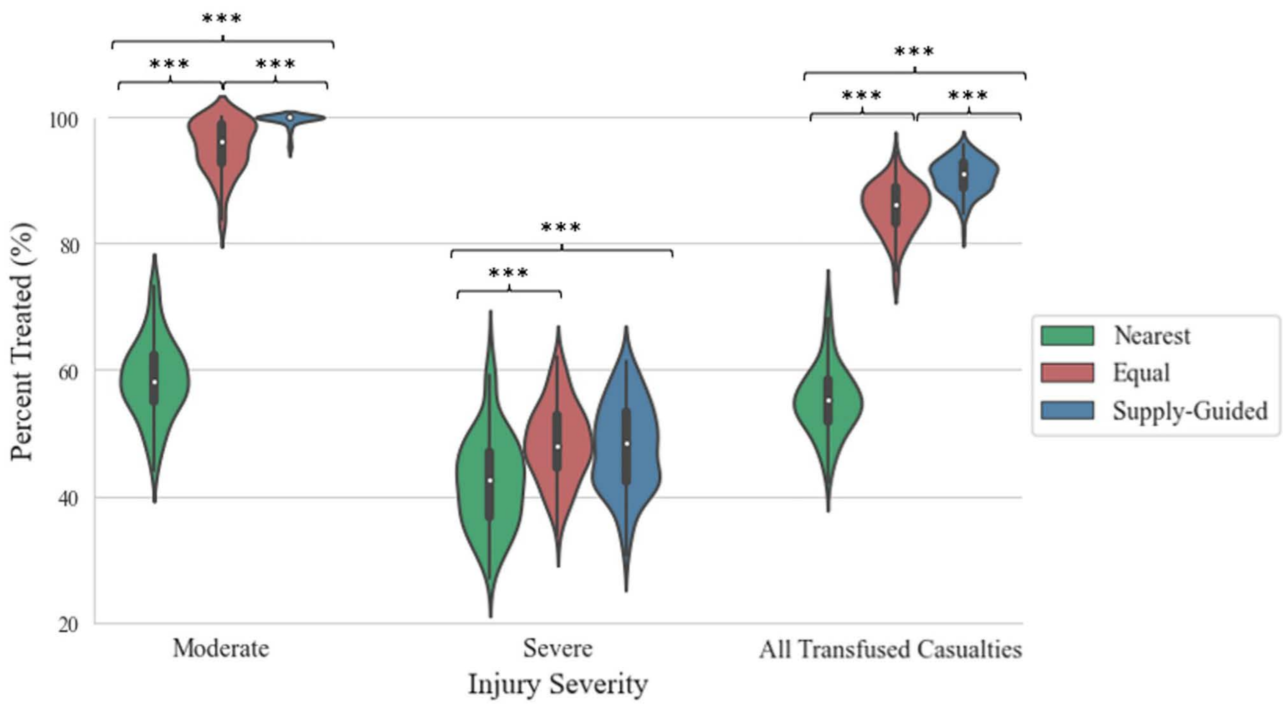

Figure 3. City-wide treatment outcomes given different triage strategies. Violin plots represent a kernel density function of the individual data points. Embedded boxplots represent the interquartile range, whiskers indicate the range of outliers, and the white dot indicates the median. ***p < 0.001.

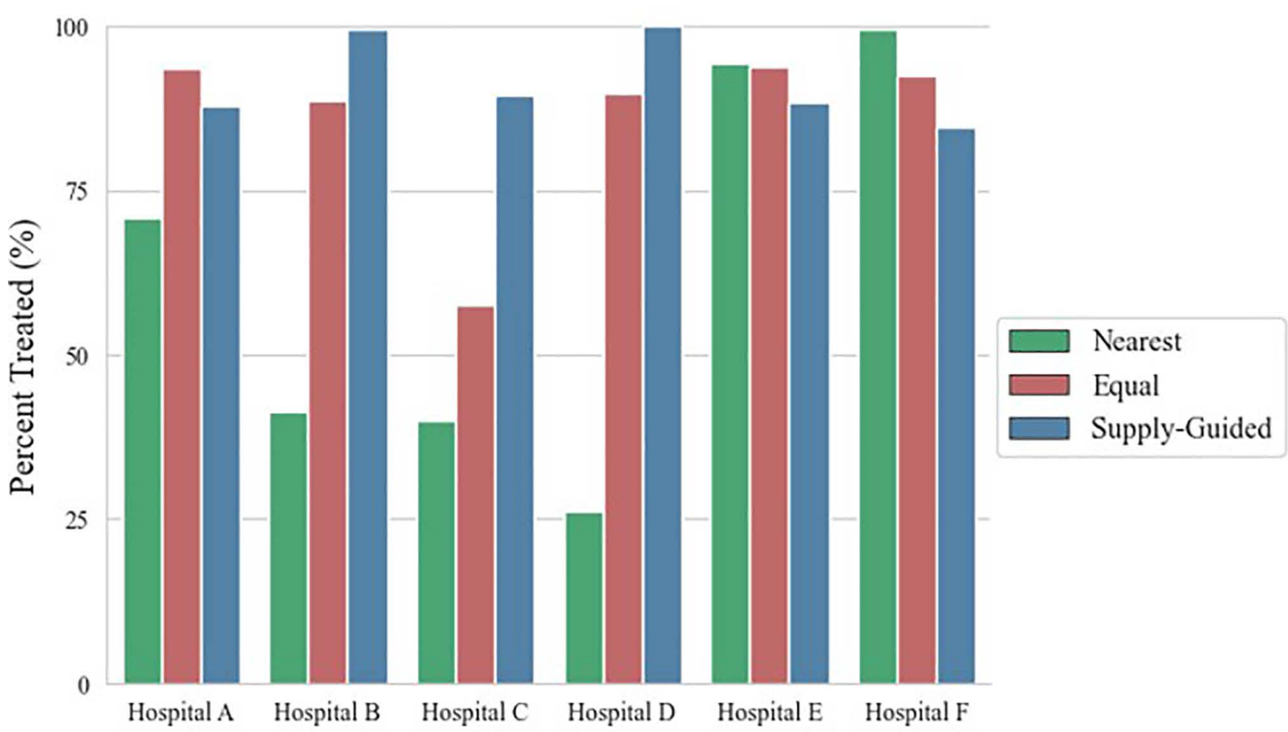

Figure 4. By-hospital treatment outcomes given different triage strategies.

Table 2. Percentage of Blood Inventories Transfused Given Nearest Triage

Blast site, time (min), component	Hospital A	Hospital B	Hospital C	Hospital D	Hospital E	Hospital F
Alpha						
60						
RBC	*	*	*	16.8 ± 4.4	4.0 ± 2.5	0.4 ± 1.4
PLAS	*	*	*	15.5 ± 3.0	9.5 ± 6.0	0.3 ± 1.0
PLT	*	*	*	83.2 ± 15.4	14.3 ± 9.3	1.1 ± 3.6
360						
RBC	*	*	*	34.8 ± 6.8	15.2 ± 3.0	12.0 ± 5.6
PLAS	*	*	*	18.9 ± 3.9	36.1 ± 7.8	8.2 ± 5.7
PLT	*	*	*	99.4 ± 0.3	54.9 ± 15.8	37.2 ± 17.5
Bravo						
60						
RBC	*	*	0.9 ± 2.8	16.5 ± 4.6	3.9 ± 2.2	*
PLAS	*	*	0.9 ± 2.6	15.8 ± 3.4	9.3 ± 5.2	*
PLT	*	*	6.8 ± 20.1	82.1 ± 16.2	13.8 ± 8.1	*
360						
RBC	*	*	17.5 ± 9.5	34.5 ± 7.0	15.6 ± 2.7	*
PLAS	*	*	13.5 ± 5.5	19.5 ± 3.9	37.3 ± 6.9	*
PLT	*	*	80.2 ± 27.2	99.4 ± 0.4	55.3 ± 13.5	*
Charlie						
60						
RBC	9.3 ± 2.1	10.1 ± 7.0	0.2 ± 1.2	*	*	*
PLAS	11.5 ± 2.3	16.4 ± 11.1	0.2 ± 1.1	*	*	*
PLT	54.9 ± 14.3	31.3 ± 22.6	1.0 ± 5.6	*	*	*
360						
RBC	19.5 ± 2.9	47.0 ± 8.9	16.2 ± 9.6	0.0 ± 0.2	*	*
PLAS	20.7 ± 2.8	54.5 ± 12.0	13.5 ± 5.3	0.0 ± 0.2	*	*
PLT	97.3 ± 6.0	98.1 ± 5.2	76.1 ± 29.2	0.1 ± 1.1	*	*
Delta						
60						
RBC	0.1 ± 0.3	26.9 ± 5.9	9.5 ± 6.8)	*	*	*
PLAS	0.1 ± 0.3	41.3 ± 9.1	9.6 ± 5.7	*	*	*
PLT	0.4 ± 1.8	78.7 ± 17.3	55.0 ± 32.1	*	*	*
360						
RBC	5.7 ± 2.8	59.1 ± 7.6	44.3 ± 11.4	*	*	*
PLAS	7.0 ± 3.4	54.3 ± 14.9	17.7 ± 4.2	*	*	*
PLT	33.1 ± 16.7	99.3 ± 1.3	98.9 ± 0.7	*	*	*

Data reported as mean ± SD.
*Hospitals that did not receive any casualties in a given mass casualty incident.
PLAS, plasma; PLT, platelets.

152 ± 17 U RBC, 151 ± 16 U PLAS, and 151 ± 16 U PLT were used. This level of PLT consumption represented as little as 9.5% of PLT inventory at hospital E and up to 48.8% of the PLT inventory at hospital C (Table 3). Six hours after an MCI, each center was treating 21 ± 2 casualties, using a total of 365 ± 23 U RBC, 346 ± 20 U PLAS, and 346 ± 20 U PLT. Hospitals at most consumed 90% of PLT inventories, and none exhausted their blood supplies. Given Equal triage, we observe that casualties in MCIs occurring at blast sites Alpha and Bravo have significantly shorter transport times on average compared with casualties in MCIs occurring at blast sites Charlie and Delta ($p < 0.001$; Table 1). Although overall transfusion treatment is similar for moderately injured casualties across all MCI locations, there is improved transfusion for severely injured casualties at Alpha (51%) and Bravo

Table 3. Percentage of Blood Inventories Transfused Given Equal Triage

Time (min), component	Hospital A	Hospital B	Hospital C	Hospital D	Hospital E	Hospital F
60						
RBC	3.0 ± 0.8	8.6 ± 2.1	8.0 ± 2.3	5.1 ± 1.3	2.7 ± 0.7	5.6 ± 1.7
PLAS	3.7 ± 0.9	14.0 ± 3.4	8.5 ± 2.2	5.1 ± 1.4	6.4 ± 1.6	3.4 ± 1.1
PLT	17.5 ± 4.2	24.8 ± 6.5	48.8 ± 14.1	26.6 ± 7.1	9.5 ± 2.4	17.6 ± 5.3
360						
RBC	7.2 ± 1.1	20.4 ± 3.1	18.9 ± 3.6	12.5 ± 2.2	6.5 ± 0.9	13.9 ± 2.6
PLAS	8.7 ± 1.3	32.2 ± 4.7	15.9 ± 2.2	12.2 ± 2.0	15.3 ± 2.2	8.3 ± 1.7
PLT	41.4 ± 6.6	57.0 ± 9.9	90.1 ± 8.6	63.2 ± 10.0	22.7 ± 3.6	43.1 ± 8.1

Data reported as mean ± SD.
PLAS, plasma; PLT, platelets.

(52%) compared with casualties at Charlie (46%) and Delta (44%; $p < 0.001$).

Supply-Guided triage resulted in each of hospitals A, E, and F receiving 5 ± 1 severely injured casualties. Within the first hour, these 3 centers received 15 ± 2 total casualties, and hospitals B, C, and D each received 10 ± 2 casualties. During the first hour, 147 ± 13 U RBC, 147 ± 13 U PLAS, and 147 ± 13 U PLT were transfused across all centers (Table 4). Six hours after an MCI, hospitals A, E, and F were each treating 23 ± 2 casualties, and hospitals B, C, and D were each treating 18 ± 2 casualties. A total of 363 ± 22 U RBC, 358 ± 21 U PLAS, and 358 ± 21 U PLT were transfused across all centers, including at most 74.4% of PLT inventories at hospital C. Hospital blood product consumption was more evenly distributed relative to consumption given either Equal or Nearest triage (Fig. 4).

DISCUSSION

The rise of MCIs worldwide has increased the likelihood of an overwhelming medical emergency in urban centers. Modern MCI planning has focused on organization, patient flow control, and logistics.[3] Although MCIs can result in large numbers of patients requiring life-saving transfusion, blood product inventory management at local hospitals has not traditionally been a part of MCI planning.[7] In this study, we constructed a discrete event simulator that modeled both patient triage and blood product transfusion services as a part of a regional MCI response. This novel simulator incorporates multiple elements intrinsic to casualty flow that enable realistic analysis of the effect of variations of these elements given different MCI conditions.

In the current study, we investigated different approaches to prehospital casualty distribution strategies across trauma centers during an MCI. The Nearest patients transport strategy was the control with which Equal and Supply-Guided were compared. Nearest, sending all patients to the nearest facility regardless of injury severity, resulted in fewer moderately injured casualties receiving complete transfusion treatment within their respective therapeutic windows. Moreover, emergency planners using Nearest triage should be particularly aware of platelet supplies, because we observed near-exhaustion of platelet inventories within the first 6 hours. These findings support careful transfusion triage in addition to the currently accepted inventory-based readiness and have been identified in research on MCI evacuation from Israel.[4] The application of real-time information tools, such as blood product and hospital

Table 4. Percentage of Blood Inventories Transfused Given Supply-Guided Triage

Time (min), component	Hospital A	Hospital B	Hospital C	Hospital D	Hospital E	Hospital F
60						
RBC	4.7 ± 0.9	3.3 ± 1.0	3.0 ± 0.7	1.9 ± 0.5	4.2 ± 0.9	8.8 ± 1.8
PLAS	5.7 ± 1.2	5.4 ± 1.6	3.3 ± 0.9	1.9 ± 0.5	10.0 ± 2.1	5.3 ± 1.3
PLT	27.2 ± 5.7	9.5 ± 3.3	18.9 ± 5.6	9.6 ± 2.5	14.7 ± 3.4	27.4 ± 6.7
360						
RBC	9.5 ± 1.2	13.9 ± 2.3	12.9 ± 2.0	8.3 ± 1.4	8.4 ± 1.2	18.1 ± 2.6
PLAS	11.6 ± 1.5	22.6 ± 3.4	13.0 ± 1.8	8.2 ± 1.3	20.1 ± 3.1	10.7 ± 2.1
PLT	55.0 ± 7.8	39.7 ± 7.9	74.4 ± 11.0	41.2 ± 7.2	29.6 ± 4.9	55.2 ± 9.2

Data reported as mean ± SD.
PLAS, plasma; PLT, platelets.

capacity dashboards, in addition to triage optimization algorithms accessible by officers on-site, could provide alternative triage strategies tailored toward favorable outcomes.

Comparing MCIs in different locations, it was noted that events with shorter average transport times to trauma centers occurring either at more centrally located venues such as Alpha (5.94 ± 0.39 minutes) or Bravo (5.78 ± 0.31 minutes), resulted in more severely injured patients receiving their transfusions within the time goal compared with events at venues that had longer transport times to hospital, such as at Charlie (9.09 ± 0.57 minutes) or Delta (9.86 ± 0.61 minutes). These differences in transport times did not impact time to receiving blood products for moderately injured casualties and may be attributed to the longer window of treatment these casualties were given, compared with severely injured casualties. These results align with recent research suggesting increased mortality with each additional minute of ground transport time in shooting victims.[44] The effect of transport times alone on casualty outcomes supports earlier transfusion services, matching suggestions made for optimal use of blood products in combat.[45] On-site storage of dried plasma (low-titer type O whole blood), prehospital tranexamic acid, and increased attention to early hemorrhage control with arterial tourniquets may improve outcomes for the severely injured.[11,45,46]

Unlike either Equal or Nearest, Supply-Guided is a complex triage strategy that incorporates information about hospital blood inventory. With this strategy, moderately injured patients are equally distributed to all centers, but severely injured patients are equally distributed to large inventory centers only, hospitals A, E, and F. This strategy aims to reduce the burden of the greater demand for transfusion services by severely injured casualties on small-inventory facilities, theoretically improving outcomes for moderately injured casualties. Supply-Guided resulted in better outcomes for moderately injured patients while not significantly impacting transfusion outcomes for the severely injured. In addition, this strategy reduced hospital insufficiency rate at small-inventory facilities, with only modest increases in large-inventory facility insufficiency. These results support previous suggestions regarding the triage of MCI casualties by injury severity, in the face of potentially increasing transport time for the severely injured.[4] Future investigation of this strategy should include the increased use of low-titer type O whole blood during MCIs which was in very limited supply at the time of our original THOR-AABB survey.[5]

Previous research of DES models of transfusion services during an MCI, such as that developed by Glasgow, emulated single-site response with RBC supply alone.[24] This model, when given comparable blood inventories and faced with similar casualty loads, resulted in the treatment of 60% of casualties with an ISS >16 within the first hour of an event, greater than our values of 42%, 48%, and 48% (Nearest, Equal, and Supply Guided, respectively). Our model, compared with previous iterations, introduced a detailed simulation of in-field casualty management and transport data unique to each MCI location and hospital. The thorough simulation of the prehospital experience in the absence of prehospital resuscitation suggests worse outcomes for severely injured casualties, providing emergency planners with an informed understanding of system-wide capacity. When comparing Glasgow's model with our own given total casualty outcomes after 6 hours, we see comparable results with Equal and Supply-Guided triage alone. Unlike the single-site models of transfusion response, ours presents a heterogeneous distribution of blood product inventories across hospitals within a health system. Future efforts in optimizing transfusion triage should therefore aim to provide casualties equitable access to transfusion services, with full respect to by-hospital blood supply.

The emphasis on blood availability in MCI response is echoed by Williams and colleagues[6] in the application of their own DES model of transfusion services, providing balanced transfusion to MCI casualties.[6] Williams suggested that most hospitals would have enough blood inventory to provide at most 2 casualties with massive transfusion, and that most hospitals would be able to treat up to 60 casualties. These results align with our by-hospital outcomes given Nearest triage, the only strategy that resulted in single sites receiving up to 50 casualties. However, we do not observe significant improvement in the treatment of severely injured casualties given Equal or Supply-Guided triage, strategies that minimize the gap between casualty demand and hospital supply. Our results suggest that, although an emphasis on improving blood inventory in emergency response planning will serve most MCI casualties, the impact on treating severely injured casualties remains limited. Further research into additional modifiable aspects of emergency response, such as a sensitivity analysis of the different parameters of our DES model, could lend insight on more effective management of this subset of victims.

Our study used blood product inventory data collected by the THOR-AABB working party.[5] It has been established that a detailed record of available blood inventories such as RBC, fresh frozen plasma, PLAS, and low-titer type O whole blood allows decision makers to better plan for events that threaten overwhelming local institutions.[28] Future work to optimize MCI and disaster response would greatly benefit from continuously updated dashboards of local blood supplies across major cities in the US. Such data collection would also permit replication of this modeling approach in other metropolitan centers to evaluate scenarios specific to that location.

Like other investigations of DES simulations in MCI response, our effort is limited by our model's orientation and focus. This model assumes complete readiness to treat with no risk of insufficient vehicles, transportation impediments such as closed roads, or hospital-level personnel, as well as enforces the necessity of prehospital triage on all patients, whereas in real life casualties may go directly to the nearest hospital after suffering an injury.[29] Patient tracking after triage has been identified as a frequent problem in MCI response, and thus real triage and transport would be less efficient than that modeled.[19] Additionally, the modeled incident was a relatively small blast resulting in only a modest number of casualties. Larger explosives or the use of multiple explosions in contained areas will cause significantly more casualties that would severely strain the blood product inventories of our largest US cities.[1-5] These considerations position our event as a best-case scenario, and future efforts with less ideal initial conditions may result in worse outcomes than the ones described. This study also did not consider other disaster scenarios such as mass shootings and did not include the role of other local nontrauma centers, such as the Veterans Affairs Health System, military hospitals, and community hospitals that would likely participate in an actual MCI. Future investigations should include a range of assumptions, such that any results reported reflect a distribution of potential outcomes rather than point estimates.

Although we can use hospital product inventory levels to estimate readiness to treat all patients during an MCI, we find that these predictions overestimate capacity to treat. Additional variables such as times for patient transport, treatment, or triage, with the necessity of provider or vehicle availability, may contribute to decreased levels of care but would be difficult to account for given simpler statistical estimates of city readiness. Criteria regarding product requirement and temporal goals may explain the impact of casualties with mixed injury severities on hospital treatment capacity, ultimately leading to worse outcomes for these patients. Simulations allow us to evaluate these different strategies given complex multifocal procedural care on a system-wide level, and thus may serve as a crucial tool in MCI emergency planning.

CONCLUSIONS

In this simulation study comparing different triage strategies, including one based on actual blood product inventories, nearest hospital triage was inferior to equal distribution or a supply-guided strategy. Patient distribution during civilian MCIs involves the complex interaction among multiple aspects of the emergency response system including both modifiable as well as nonmodifiable factors. Simulation studies such as this allow disaster response experts to untangle some of this complexity. Disaster response leaders in US urban areas should consider modeling different MCI scenarios and casualty numbers to determine optimal triage strategies for their region given hospital numbers, locations, and blood product inventories.

APPENDIX

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