Evaluating the Effect of Bleeding Control Kit Locations for a Mass Casualty Incident Using Discrete Event Simulation

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ABSTRACT

The purpose of this study was to develop a simulation model to evaluate bleeding control kit location strategies for a mass casualty incident scenario. Specifically, the event simulated was an explosion at a large sports arena. The model included a representation of the arena itself, simulated crowd movements following the detonation of an improvised explosive device, injuries and treatments, and different ways for immediate responders to help injured patients using tourniquets. The simulation model gave logically consistent results in the validation scenarios and the simulation outcomes were in line with the expected outcomes. The results of the different tourniquet location scenarios indicated that decentralized placement (more than one location) is better, easy access is important (between rather than at emergency exits) and that an increased number of available tourniquets will result in an increased number of survivors.

Keywords

Simulation, Mass Casualty Incident, Tourniquet, Stop the Bleed, Bleeding Control Kit Placement.

INTRODUCTION

Trauma, which is physical injury to the human body, is the worldwide leading cause of death for people between 15-45 years old (Haagsma et al., 2015). Among these deaths, there are potentially survivable deaths in which the deceased might have survived if prompt medical interventions had been used prior to the arrival of an ambulance (Chiara et al., 2002; Goolsby et al., 2018; Oliver et al., 2017). Bleeding control is one such essential first aid measure. Uncontrolled severe bleeding can lead to death within minutes. Retrospective studies using autopsy reports estimate that up to half of the studied trauma-related deaths were potentially preventable had the victims received adequate pre-hospital care, such as bleeding control interventions (Oliver et al., 2017; Gedeborg et al., 2012).

The Stop the Bleed (STB) campaign translates battlefield medical lessons learned from recent wars in Iraq and Afghanistan, during which an estimated 1000-2000 lives were saved by prompt tourniquet use, to benefit the civilian public (Rasmussen, Baer & Goolsby, 2016; JEMS Staff, 2016; Blackbourne et al., 2012). The STB campaign promotes the civilian use of bleeding-controlling techniques such as direct pressure, tourniquets, and hemostatic dressings. The STB campaign emphasizes that these bleeding control skills and equipment are generally applicable for any traumatic bleeding regardless of cause (Levy & Jacobs, 2016). However, a frequently discussed scenario is a mass casualty incident following a major accident or antagonistic attack. For such a scenario, there is a need to enable and empower laypersons to act as well as strategically place bleeding control kits, containing tourniquets and other hemorrhage controlling equipment, in public places where they might be needed.

Several challenging questions arise; how many kits, how much equipment should each kit contain and where should they be placed to be most effective? Since no formal widely accepted guidelines are available, Goolsby et al. (2019) reviewed available trauma databases to estimate how many victims that would need a bleeding control kits in intentional mass casualty scenarios. Based on the database review, Goolsby et al. estimate that a maximum of 40% of the casualties might potentially benefit from immediate responder external hemorrhage control and based on the largest typical mean number of victims in such a scenario (51 individuals), it was recommended that kits should include equipment to treat 20 people. The authors also recommend that larger public venues should consider placing multiple kits and plan how to distribute the equipment.

A similar initiative is the training, empowering and equipping of immediate responders to handle cardiac arrests in the community. Public access defibrillators can now be found in many public venues. Optimal distributions of public automated external defibrillators (AEDs) has been studied, where coffee shops, ATMs and other easily accessed locations where many people congregate are recommended for Public AED programs (Becker et al., 1998; Dahan et al., 2016; Sun et al., 2016; Sun et al., 2017). However, there are key differences in the scenarios that require an AED versus a bleeding control kit. Cardiac arrests happen to a single person at a time, resulting in an immediate responder-to-patient ratio equal to or greater than one. Events that lead to severe hemorrhage, on the other hand, are more likely to have multiple victims in a space with large crowds that want to evacuate the site. Thus, even if there are experiences to draw from it is important to establish specific models for Stop the Bleed-scenarios.

To improve the accuracy and be able to provide recommendations to public venues, there is a need to model and simulate typical scenarios that we aim to prepare and equip the immediate responders for. These models should include relatively high detail, which involves a comprehensive model of the typical public locations where such events are likely to occur, behavior of crowds and immediate responders, as well as the injuries, equipment requirements and equipment placements. The goal of this study was therefore to develop a simulation model that allows evaluation of bleeding control kit location strategies in a mass casualty incident scenario. Specifically, the simulation model focused on the issue of efficient location of bleeding control kits at a concert in a sports arena.

SIMULATION MODEL

Discrete event simulation (DES) was used to model and simulate the scenario. DES models are dynamic such that the modelled system changes its state at instantaneous moments in time and the time interval between the state changes can be of arbitrary length. In DES models, people can be modelled as separate entities with individual characteristics and history. DES models can deal with the uncertainty in the model parameters by using random numbers drawn from different probability distributions. Due to this, DES models require many runs, called replications, in order to estimate the variation in scenario outcomes.

The Scenario

In a fictitious scenario, a concert is taking place at an unspecified arena (e.g. soccer or football stadium), with 16,200 people in attendance, mainly as standing audience. During the concert, a detonation of one or more improvised explosive device(s) (IED) takes place somewhere in the audience, which results in a number of people suffering injuries of varying degree. Some die immediately, some are injured, and most are not affected by the blast. In the scenario, the structure itself is not compromised by the explosion. This scenario corresponds to a mass casualty event following an antagonistic attack in the public without an ongoing threat.

Some of the spectators will act as volunteers and will try to help the injured people. The staff is assumed to have received first aid training and will also try to help. Ordinary concert spectators will, after a certain reaction time delay, try to reach one of the emergency exits and leave the arena. The arena has bleeding control kits at different locations, and it is the placement of these that is systematically varied across the different simulation scenarios (explained further in the section on Experimental setup). For the current model, only tourniquets were included in the bleeding control kits although real kits would most likely include several other pieces of equipment as well, e.g. gauze, gloves, and wound dressings. However, modeling the effect of all these various pieces of equipment, on different types of injuries, was beyond the scope of the current study. Volunteers will try to discover the location of the bleeding control kits and then move to that location in order to retrieve a tourniquet. Staff is assumed to know the kit placement and will therefore need shorter time to retrieve them. Because not all volunteers are assumed to be familiar with the use of tourniquets, only a fraction of them will proceed to retrieve the tourniquets, while the rest will try to reach the injured and apply pressure to the wound in order to slow the bleeding. Upon the retrieval of the tourniquet, volunteers and staff will move to the location of injured persons and help them by applying the tourniquet, without any prioritization (triage) according to severity of injury. After the application of the tourniquets, volunteers will leave the arena through one of the exits while some of the staff will stay at the site and some will help with the evacuation of spectators. Those volunteers that apply pressure to the wound will keep doing so until the tourniquet is applied, or the injured person dies.

If the tourniquet is not found at the first chosen location, a fraction of volunteers and staff will look for it at other places one or two times. If no tourniquets are found, the volunteers will leave the arena while staff will move to the incident site and possibly stay there. In this model, any one person (staff or volunteer) only takes one tourniquet with them. Alternative ways of distributing the tourniquets, or bleeding control kits, such as one person retrieving some or all kits from one location and re-distributing them to wounded persons along a route or a few volunteers forming ad-hoc teams to treat multiple patients were not modeled in the current study although they are interesting options for future research. The scenario ends with arrival of ambulances to the incident site 25 minutes after the explosion takes place. These 25 minutes is a simplified representation of the process of alerting emergency dispatch service, all ambulances response time, and individual paramedics and nurses getting past the evacuating crowd to all patients and treating them. A rather long ambulance response time was deliberately chosen, to ensure that that the existence of bleeding control kits would have an impact on the result.

The Arena

The whole arena was divided in three types of zones – spectator zones z_1-z_{12}, outer (transit) zones u_1-u_{18}, and exits e_1-e_{12} (see Figure 1).

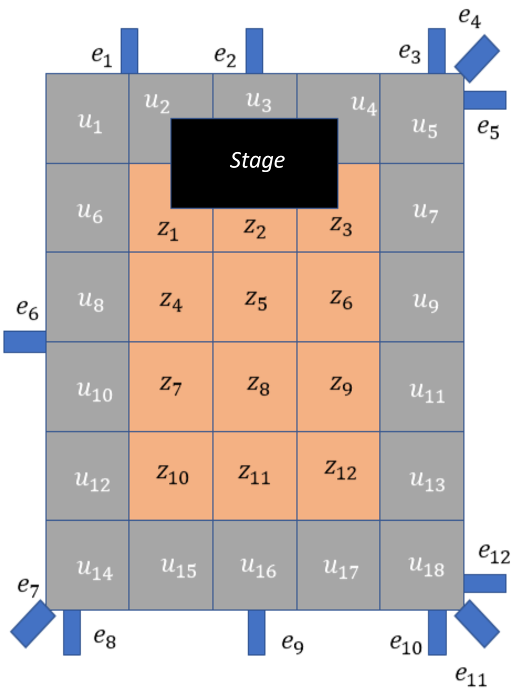

Figure 1. The layout of the arena, divided in to spectator zones (z), outer zones (u) and exits (e).

The spectators were randomly distributed in zones z_1-z_{12} in the beginning of the scenario, while outer zones and exits were empty. The zones closer to the stage were assumed to have more spectators than more distant zones (Säterhed et al., 2015). Spectator zones and outer zones were 20*20 meters wide each, and the stage size was 20*40 meters. The width of the exits e_1-e_{12} were dimensioned according to the Swedish requirements for the venues of this size (Boverket, 2006; Boverket, 2014), which is one meter of emergency exit per 150 people. Given that there were 12 emergency exits this resulted in 9 meters wide emergency exits. The spectator density in each zone is summarized in Table 1.

Table 1. Spectator density

Spectator zone	Spectator density	Area (m2)	Number of spectators
z1	5	300	1,500
z2	6	200	1,200
z3	5	300	1,500
z4	4	400	1,600
z5	5	400	2,000
z6	4	400	1,600
z7	3	400	1,200
z8	4	400	1,600
z9	3	400	1,200
z10	2	400	800
z11	3	400	1,200
z12	2	400	800
Total		4,400	16,200

There were four types of people in the model: staff, ordinary spectators, volunteers (spectators that will help the injured), and injured. The number of staff and volunteers is based on recommendations and previous studies (Säterhed et al., 2015). It was assumed that there would be 276 security staff and other individuals who are trained in first aid and tourniquet application, spread out evenly in all spectator zones. In a study by Schroll et al. (2015) they found that 20% of patients had an improvised tourniquet placed on them before emergency services arrived on the scene. Given the differences in the nature and the size of the event, as well as the ongoing evacuation, we assumed that between 3-6% of spectators would be aware that there are injured persons and also willing to help them.

Modelling Injuries and Bleeding

The total number of people injured in an explosion is difficult to estimate due to wide variation in possible IEDs used in such scenarios. The actual number of injured people will depend on the number and type of explosive devices, which is obviously difficult to predict. We therefore assume a wide variation of possible number of casualties by using a uniform distribution for the total number of injured, where it is equally likely that between 20% to 90% of people in the zone of the explosion are injured. It was assumed that only those in the zone where the explosion occurs would be injured. Whether the injuries are due to one larger explosion or several, smaller and simultaneous explosions within the same zone is in this case irrelevant as both cases would result in the same injury sets. The explosion was equally likely to occur in any of the 12 spectator zones. Only spectators who are injured are modeled, not spectators that would be immediately killed by the explosion.

The injuries were further classified as fatal (12%), severe (22%) or light (66%), based on estimations in a report by the Swedish Civil Contingencies Agency (MSB, 2014). It was assumed that 32% of fatally injured could potentially survive and 25% of these would have injuries in the extremities (Smith et al., 2018), in which case the application of a tourniquet would be advantageous. Goolsby et al. (2019) concluded that 40% of the injured in antagonistic bombings could have benefited from application of a tourniquet. Therefore, for the categories of severely and lightly injured, 40% of the respective category were assumed to have a bleeding injury. In our model, fatal injuries were modelled as massive, life threatening bleeding with a bleeding rate of 400 ml per minute. For the light injuries the bleeding rate was set to 80 ml per minute, and for the severe injuries to 200 ml per minute. The bleeding rates were based on Tjardes and Luecking (2018), who state that a massive, femoral artery bleeding can be upwards of 500 or even up to 1,500 ml per minute.

A critical bleeding volume limit was set at 2,500 ml, and all injured people who reached this volume were assumed having died from traumatic hemorrhage. This is of course a simplification as a life-threatening bleeding depends on, among other things, gender, body size, age, prior health history, etc., and is therefore very individual. The volume limit was set based on published guidelines in advanced trauma life support blood loss of a class IV life-threatening shock, which is 40% of the total blood volume, plus an additional 25%. For an adult male weighing 70 kg with 5,000 ml circulating blood volume that is 2,000 ml, plus the 25% which gives 2,500 ml (American

College of Surgeons Committee on Trauma, 2017; Mutschler et al., 2013). A bleeding of 400 ml per minute (fatal category) is then in line with the Tactical Combat Casualty Care (TCCC) guideline that life-saving medical interventions following trauma must be given within 5 minutes, as the critical volume loss would be reached at 6 minutes and 15 seconds into the simulation.

Modelling Post-Explosion Actions and Movement of People

According to Sime (1986) there are three different components of total evacuation time: situation discovery time, reaction time and travel time. The first two components are hard to estimate (Graat et al., 1999) and here the time to identify the location of the tourniquets must be added as well. Discovery time was assumed to increase with distance from the blast zone by 2.5 seconds per zone. Triangular probability distributions were used to generate reaction time and location identification time, and these times were shorter for staff compared to volunteers.

Movement of people was assumed to always occur from the center of one zone to the center of another, adjacent zone. The travel time was affected by the density of people in each traversed zone – the higher the density, the slower the movement speed. The speed was drawn from an array of 8 different probability distributions, based on the actual density in the traversed zone. Consequently, the average speeds varied from 1.5 m/s at the lowest density to 0.05 m/s at the highest density. The density was updated dynamically for all zones as the simulation progressed. Movement was only allowed vertically and horizontally (not diagonally) and the shortest path between two zones was predefined in a static matrix in the simulation model, which means that the actual movement trajectory did not depend on the density of people in the route (see Figure 2). Every spectator zone had a list of possible (closest) emergency exit destinations, and these were assigned randomly to each spectator with higher probability for those exits that were closer.

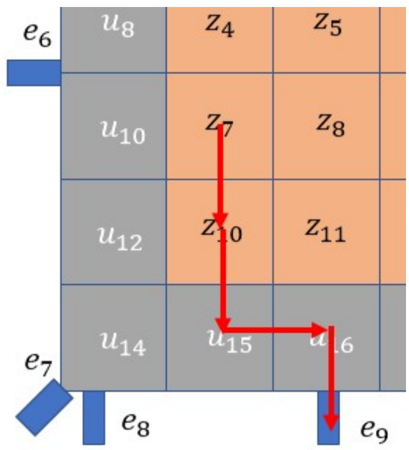

Figure 2. Movement trajectory from spectator zone z_7 to exit e_9.

Emergency exits were narrow sections in the evacuation path and the speed of movement through these exits was determined by the width of these exits. Those spectators who arrived at the emergency exit but had not yet moved through it were assumed to occupy the outer zone(s) ***u*** closest to the corresponding exit. The movement speed through the outer zones was calculated using the same formula as for the spectator zones.

Bleeding Control and Tourniquet Application

Upon collection of tourniquets, the staff and volunteers would move towards the injured people using the same method as described in the section above. Tourniquet application time was based on measurements made during bleeding control training sessions (Prytz & Jonson, 2019), and as drawn from a triangular distribution centered on 65 seconds (37-107) for trained staff, and 120 seconds (107-180) for volunteers.

When the tourniquet was applied, the bleeding was assumed to stop. By applying direct pressure, the bleeding rate was assumed to reduce by 40% based on trauma expert opinion and related research (Kozen et al., 2008; Slevin et al., 2019). If only pressure was applied, but no tourniquet, severely injured persons would eventually die from blood loss in this scenario.

Experimental Setup

The simulation model was implemented in the commercially available simulation software ARENA (Rockwell Automation). The model was run for 563 replications in order to have a 99% confidence interval for the number of people dying from blood loss of less than ± 2, when evaluating the tourniquet placement alternatives. The model had two main inputs: placement of tourniquets (zone of location) and number of tourniquets at each location. All other model parameters could also be changed for calibration and validation purposes including the sensitivity analysis. The main output from the model was the number of people that died from blood loss (bleed out) before the arrival of ambulances to the incident site.

The following alternative placement strategies were tested in the model:

a) Following the recommendation for the number of tourniquets by Goolsby et al. (2019) and the landmark-based strategy used for AED placement (Dahan et al., 2016), 20 tourniquets were placed at each of the 12 emergency exits, resulting in 240 tourniquets in total. To make the results comparable, the same total amount of tourniquets was used in all other alternative placements as well.

b) In order to avoid the crowding at the emergency exits and provide easier access, the tourniquets are placed between the emergency exits, resulting in 10 locations with 24 tourniquets each.

c) The tourniquets are placed in 4 locations between the emergency exits (60 per location).

d) All 240 tourniquets are placed in a single location, at one emergency exit.

e) All 240 tourniquets are placed in a single location, between two emergency exits, to avoid the crowding.

RESULTS

The results can be divided into three parts: 1) Calibration and validation, 2) Study of different tourniquet placements, and 3) Sensitivity analysis. In the default setting, 240 tourniquets are available, and their placement is the main field of study. The number of staff that will try to help the injured are always 276, while the number of volunteers vary between the simulation runs. Each scenario was run for 563 replications, and the results are presented as mean values and standard deviations calculated based on these replications.

Calibration and validation

Calibration and validation are necessary to ensure that the model behavior is realistic and that the results can be considered useful for the purpose of the study.

One of the best ways to verify and validate a simulation model is to examine if it can reproduce a real (historical) case. However, necessary data is lacking for the specific scenario used in this study. Instead, several tests were run where the results could be easily predicted. These runs are summarized in Table 2.

Table 2. Validation runs

Scenario		Expected outcome	Simulation outcome
1a	No help available	The number of persons bleeding to death should correspond to the number of persons with serious injuries	Mean number of deaths was 265.51, which is as expected
1b	No tourniquets available	Since some persons will get help by volunteers and staff applying pressure on the wounds, fewer people are expected to bleed out than in the previous scenario	Mean number of deaths was 129.10, which can be considered reasonable as 189.41 persons received direct pressure
1c	120 tourniquets available	With available tourniquets, the number of deaths due to hemorrhage should decrease	Mean number of deaths was 47.52, which can be considered reasonable
1d	360 tourniquets available	With even more tourniquets, the number of hemorrhage deaths should decrease further	Mean number of deaths was 3.20
1e	Unlimited supply of tourniquets	The number of deaths should be small but not zero as some will bleed out very	Mean number of deaths was 2.29

		quickly	
1f	No injuries	If nobody is injured in the explosion, the number of evacuated persons should be the total number of persons minus the staff staying behind, and nobody should need treatment or bleed out	As expected

As can be seen in Table 2, the number of people dying as a result of blood loss decreases when volunteers and staff apply pressure (Scenario 1b), and even more when tourniquets are available and used. A larger number of available tourniquets (Scenario 1c-1e) gives the ability to help more people in the simulation runs where there are a lot of injured, and thus the mean number of hemorrhage deaths decreases with the number of available tourniquets. However, even with an unlimited supply of tourniquets (Scenario 1f), some people will die. This is because the bottleneck instead will become the number of available staff and volunteers applying pressure and tourniquets, and that the time to find and apply a tourniquet might be too long for a severely injured person.

Study of different tourniquet placements

Five different scenarios were constructed where only the placement of the 240 tourniquets differ, where:

- Scenario 2a: The tourniquets are placed at the emergency exits (12 locations)
- Scenario 2b: The tourniquets are placed between the emergency exits (10 locations)
- Scenario 2c: The tourniquets are placed in fewer locations between the emergency exists (4 locations)
- Scenario 2d: The tourniquets are placed in one location, at an emergency exit (1 locations)
- Scenario 2e: The tourniquets are placed in one location, between two emergency exits (1 locations)

A selection of output parameters from these runs are presented in Table 3. A treatable person is someone injured in the explosion, with an injury that is treatable with a tourniquet. For all scenarios, the same event is simulated in each replication for each scenario, giving the same number of treatable persons and the same number of volunteers. That is, for each replication the number of treatable persons and volunteers is identical for all scenarios, but each replication has different number of treatable persons and volunteers. These are reported in Row 2 and 3 in Table 3. As can be seen, the total number of treatable persons varied between 133 and 437, while the number of volunteers varied between 573 and 776. Given that the available number of staff always was 276, there were always more people helping than the number of people injured. Thus, the reason that people died in the simulation was due to it taking too long to receive help, or that the number of available tourniquets was too low.

Table 3. Results of different placement alternatives

Scenario	Mean value	Standard deviation	Confidence interval (99%)	Min value	Max value
All (Total number of treatable persons)	265.68	71.1	[257.96, 273.4]	133	437
All (Total number of volunteers)	658.45	28.06	[655.4, 661.5]	573	776
Scenario 2a: Placement at exits	13.36	14.85	[11.75, 14.97]	0	79
Scenario 2b: Placement between exits	12.27	14.20	[10.73, 13.81]	0	69
Scenario 2c: Placement at fewer locations	12.23	14.23	[10.68, 13.78]	0	71
Scenario 2e: Placement at one location, at exit	17.30	17.66	[15.38, 19.22]	0	87
Scenario 2f: Placement at one location, between exits	12.66	14.59	[11.08, 14.24]	0	72

Note: The numbers for Scenarios 2a-2f represents the number of deceased from blood loss.

The results in Table 3 show that the number of hemorrhagic deaths varies between the different scenarios. More people die when the tourniquets are located at emergency exits (Scenarios 2a and 2e), as the crowd of people trying to leave the arena reduced the movement speed for those fetching the tourniquets. Scenario 2e has substantially higher deaths than all other scenarios. The differences between Scenarios 2b, 2c and 2f are negligible, and thus it seems that it does not matter much where the tourniquets are located, as long as it is easy to access them. The slightly higher number of deaths in Scenario 2f, might be due to increased travel distance when fetching a tourniquet when all tourniquets are located at the same spot.

Sensitivity analysis

Additional runs were performed to see how the results are affected by parameter changes. For each run, one of the parameters listed in Table 4, below, was changed to investigate the effects on hemorrhagic deaths. In all these runs, 240 tourniquets were located at the 12 emergency exits (i.e. Scenario 2a). The results can be found in Table 4.

Table 4. Results when changing input parameters

		Number of hemorrhage deaths				
Scenario	**Parameter change**	**Mean value**	**Standard deviation**	**Confidence interval (99%)**	**Min value**	**Max value**
3a	No changes (base scenario)	13.36	14.85	[11.75, 14.97]	0	79
3b	Movement speed +75%	11.71	14.23	[10.17, 13.25]	0	71
3c	Movement speed -75%	20.36	20.02	[18.19, 22.53]	0	95
3d	Increased allowed blood loss before death (+500 ml)	12.32	14.53	[10.74, 13.90]	0	78
3e	Decreased allowed blood loss before death (-500 ml)	15.59	15.11	[13.95, 17.23]	0	77
3f	Bleeding reduction when applying pressure (+20 percentage units; 40->60%)	3.94	6.18	[3.27, 4.61]	0	32
3g	Bleeding reduction when applying pressure (-20 percentage units; 40->20%)	14.49	14.87	[12.88, 16.10]	0	79
3h	Longer time for finding tourniquets (+50%)	13.88	15.20	[12.23, 15.53]	0	74
3i	Shorter time for finding tourniquets (-50%)	12.78	14.73	[11.18, 14.38]	0	76
3j	More staff available (+70%)	12.96	14.90	[11.34, 14.58]	0	73
3k	Fewer staff available (-70%)	13.86	15.07	[12.22, 15.50]	0	78
3l	More volunteers helping (+50%)	12.91	13.99	[11.39, 14.43]	0	63
3m	Fewer volunteers helping (-50%)	18.29	26.09	[15.46, 21.12]	0	138
3n	Longer tourniquet application time (+70%)	14.33	15.11	[12.69, 15.97]	0	80
3o	Shorter tourniquet application time (+70%)	12.61	14.68	[11.02, 14.20]	0	77

Table 4 shows that the results are quite insensitive to parameter changes that should improve the survival rate, such as increased movement speed (3b), shorter time to find tourniquets (3i), more staff and volunteers (3j and 3l) and shorter time to apply tourniquets (3o). The one scenario that stands out in this regard is making the direct pressure more effective (3f), which is associated with a substantial reduction in mortality. Parameter changes that resulted in worsened outcomes were decreased movement speed (3c) or fewer volunteers helping (3m). The result in 3c might be explained by the increased crowding effect at the emergency exits, as some people evacuating the arena now moves very slowly. Thus, it takes much longer time to access a tourniquet located by an emergency exit. The result in 3m is due to fewer volunteers applying pressure, which leads to a substantially higher mortality rate.

DISCUSSION

The current simulation model showed logically consistent results in the validation scenarios, and the simulation outcomes were in line with the expected outcomes. The results of the different tourniquet placements, in scenarios 2a-f, showed minor variations. The two scenarios where the kits were placed at the emergency exits were associated with higher mortality than those where the kits were placed between emergency exits. The results from the sensitivity analyses showed that the outcome would be worsened if walking speed was reduced and fewer volunteers assisted, and that the outcome would be better if direct pressure slowed the bleeding rate to a greater extent. The time to find tourniquets, tourniquet application time, and number of staff did not have a practically significant impact. In summary, it is probably better to 1) have tourniquets in more than one place, and 2) avoid placing the tourniquets by emergency exists or other places that might become crowded.

In contrast to prior work regarding the placement of AEDs, e.g. Sun et al. (2016; 2017), there are other dynamic aspects to consider when determining the placement of bleeding control kits. The simulation model used in the current study showed, for example, that the movement of the crowd makes placement at exits less effective as immediate responders who are trying to reach a bleeding control kit and return to an injured person must move against the crowds. Crowd movement is not necessarily a factor in AED placement. This study shows that further work is needed to analyze what lessons from AED placements are applicable in bleeding control kit placement, and what lessons that are not applicable.

Prior work on mass casualty incident management, injuries, and bleeding control kit equipment and placement, e.g. Goolsby et al. (2019), were incorporated into the model, in terms of, for instance, the number of optimal tourniquets in a kit. Other factors were systematically varied, such as the placement of the tourniquets. However, the lack of prior data does limit the model and the validity of the results. The efforts of Goolsby et al. (2019) to determine bleeding control kit specifications based on trauma database reviews is to date the most comprehensive and structured effort to provide guidelines for emergency planners looking to equip their facilities with bleeding control kits. The current study shows that simulation models provide a useful complimentary method to systematically test such guidelines.

Regarding the optimal number of tourniquets, this is not something that is studied here. The main reason is that increasing the number of tourniquets will always be beneficial if no costs are considered, even if the marginal effect will go towards zero after a while. Therefore, in order to estimate the number of tourniquets that should be placed in each location it is necessary to calculate the cost for each bleeding control kit, which might include a fixed cost for setting up a location. This, in turn, must be set in relation to the expected (monetary) benefits from having the kits, and having people trained in using them, which is an interesting avenue for further research. An alternative might be to assume a fixed budget for kits and for training, and then try to decide how to best utilize this.

A limitation of the current study is that the simulation model still has relatively low resolution and only includes some of the variables that are likely to affect the use of tourniquets and subsequent patient outcomes in a mass casualty incident. The results from the sensitivity analyses support the notion that the model must include more factors for more rigorous and valid simulation of bleeding control kit placement. Suitable variables to explore in future models are more advanced physiological models to simulate other types of injuries that requires care, and factors such as bleeding control kit distribution strategies, movement and evacuation of injured patients, and professional responder actions in collaboration with immediate responders. One example is the effect of stampeding and crowd crushes, which might hinder responders and cause additional injuries that need to be treated.

Another limitation is the deliberate constraint to only model and study a sports stadium setting and not extend this to other public places such as stores, schools or airports. The choice of using a sports stadium was inspired by the work of Goralnick and colleagues (Goralnick et al., 2018) who trained 465 staff at a major sports stadium in Massachusetts in bleeding control methods, including tourniquet application. It also served well as a first attempt to create a model to test bleeding control kit placement strategies. Further research is needed to create accurate and valid models of other settings and scenarios. Additionally, the current study was based on a fictitious event. Adapting the model to be able to replicate a historical event would facilitate a more thorough validation and provide better estimates of the benefits of the Stop the Bleed initiative.

CONCLUSION

In the current study, a model was developed of a mass casualty incident at a concert in a sports arena. The model included a representation of the arena itself, crowd movement following an explosion, injuries and treatments, and different ways for immediate responders to help injured patients using bleeding control kits. The model behaved as expected in the validation test cases and was then used to test the effect of different bleeding control kit locations. The results from the simulation model showed that:

- Decentralized placement (i.e., more locations) seems preferable to centralized placement (i.e., one location)
- Actual location plays a role, particularly with regards to easy access during crowd movement, such that placements *between* emergency exits is preferable to placement *at* emergency exits if there are few kits available
- The total number of available tourniquets matters
- Improved efficacy of direct pressure has a significant positive effect on survival rates, indicating the importance of this method for Stop the Bleed educational campaigns

These results must be interpreted with respect to the resolution and validity of the current simulation model. However, the model does show that relying on past research on AED placement (e.g., a landmark-based strategy) for bleeding control kit placement can result in unexpected problems.

The current study also shows, by example, that using simulation is a meaningful and valuable method to study the effects of the number and placement of bleeding control kits to support immediate responders in mass casualty incidents. Avenues for future work includes increasing the accuracy of the model by reducing the uncertainties and number of assumptions as well as testing the model in scenarios where real life data is available in order to further validate the model. Further factors such as crowd crushing, use of improvised tourniquets and other alternative hemorrhage control methods, and the willingness of people to act in different scenarios to help others are all relevant for future research. A developed and validated simulation model could be implemented as a practical tool for security and event planners.

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DISCLAIMER

This article is the authors' opinions and does not represent the official policy or position of the Uniformed Services University, US Defense Department, or US Government.

CONFLICTS OF INTEREST

CG has a patent pending for "tourniquet and method of use."

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