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Abstract: The medical response to mass casualty terrorist bombings (MCTB) has received extensive treatment in the trauma and emergency medicine literature over the past 25 years. An effective medical response must consider four fundamental aspects: (1) the objective of the response, (2) the typical injury pattern, (3) triage, and (4) the delivery of care. This report discusses the key components of each of these aspects, identifying points of consensus and contention and articulating unresolved research questions. Particular attention is given to the triage process because of its importance to the overall response and the array of differing opinions on how, where, and by whom it should be completed. Mathematical models of the trauma system during an MCTB are limited, and we propose developing such models to provide insight into the articulated research questions.

Keywords: mass casualty incident, terrorist bombing, triage, trauma system, emergency response planning, mathematical modeling

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The management of the medical response to mass casualty terrorist bombings (MCTB) has recently received an increasing amount of attention in the trauma and emergency medicine literature. The aim of this literature is to guide hospitals, in particular emergency departments (ED) and trauma centers, in the development of disaster response plans and protocols. MCTBs are a special form of mass casualty incident (MCI), and like other types of MCIs (such as natural disasters) are often accompanied by a large surge of victims with potentially life-threatening injuries requiring medical attention [14]. However, there is ample evidence showing that the victims of terrorist bombings present a specific injury pattern that distinguishes them from conventional trauma patients [19], [20]. This distinct injury pattern validates the need to research the medical response to MCTBs as a unique problem not covered by traditional MCI response planning.

Frykberg and Tepas published one of the earliest analyses of injury patterns observed after terrorist bombings, and their results have guided nearly all subsequent research published in this area [9]. Their initial work compiles data from existing studies on 220 incidents occurring between 1969 and 1983, and a follow up study by Frykberg adds data from several prominent incidents between 1986 and 2001 [10]. These studies and others suggest four fundamental aspects of the medical response that must be considered in the development of a response plan: (1) objective of medical response, (2) description and knowledge of the typical injury patterns, (3) triage, i.e. determining which victims are in need of immediate care, and (4) delivery of medical care.

Objective of Response

Most would agree that the generic goal of the medical response to an MCI is to "save as many lives as possible," but there is no such consensus on exactly how this goal should translate to objectives for the delivery of medical care. The literature on this point falls into two main camps, those who advocate shifting focus from "doing the greatest good for each individual to doing the greatest good for the greatest number of people" ([3], [10], [11], [13]) and those who advocate providing severely wounded victims with "a level of care that approximates the level of care provided to similar trauma patients under normal circumstances" ([5], [15], [16], [17]). On the surface, the extent to which these two goals are contradictory is not immediately clear, but the difference becomes apparent when considering the treatment of the most severely wounded victims (who are not likely to survive even with optimal medical care).

The vagueness of these objectives makes them difficult to measure. However, some metrics have been proposed that allow health care providers and researchers to judge the efficacy of the medical response to an MCI. The *critical mortality rate* measures the percentage of severely wounded patients who die after their medical care has begun [9], [12]. This metric most closely aligns with the first objective above. The other metric, which aligns with the second objective, focuses on the *surge capacity* of a hospital, or the hospital's capacity to treat newly-arriving severely wounded victims without degradation in the care they receive. The recent trend in the literature states surge capacity as an arrival rate and requires a method for measuring quality of care [6], [15], [17]. In a recent simulation model, Hirshberg et al. determine the quality of care by assigning relative scores to the trauma teams assembled for severely injured patients [17].

Patterns of Injury Severity

While the magnitude of a MCTB is often judged publicly by the number of immediate casualties, the scope of the problem facing an ED or trauma center in the aftermath of such an event depends not on the immediate mortality rate but on the number of injured victims who arrive at the hospital seeking treatment [15]. Nearly all analyses of terrorist bombing injury severity patterns show that between 10 and 20 percent of injured survivors are severely wounded [2], [4], [5], [6], [9], [10], [20], [22].

Several factors relating to the circumstances of the attacks have been shown to correlate with injury severity patterns. The number of immediate deaths is not surprisingly tied to the magnitude of the explosion, but other key factors include whether the bomb was detonated in an outdoor space or in a confined area and the collapse of any buildings or other structures [10]. Of these factors, the difference between open and confined spaces is the most significant in determining the rate of severely injured victims among the immediate survivors, with explosions taking place in confined spaces (such as buses, restaurants, and crowded marketplaces) leading to higher numbers of severely wounded [9], [10].

Triage

Both of the objectives discussed above focus the primary efforts of the trauma response on the effective delivery of life-saving care to those immediate survivors identified as severely

wounded. For this reason the triage process, which serves to separate the severely wounded from the other immediate survivors, is perhaps the most-discussed component of disaster planning. Varying opinions can be found in the literature on nearly every aspect of the triage process, including how and where it should be conducted, who should conduct it, and how accurate it must be to meet the overall objective. Armstrong et al. claim that the characteristics of an effective triage plan are simplicity, time efficiency, predictive validity, reliability, and accuracy, and all of the opinions on triage discussed below aim to improve the process in some or all of these aspects [3].

In general, there are five triage categories based on the level of treatment the victim requires: (1) those who require immediate care, (2) those whose care may be safely delayed, (3) those who require minimal care, often referred to as the walking wounded, (4) those who are so severely wounded that they are unlikely to live even with medical care, referred to as expectant, and (5) those who are dead [10], [13]. However, in the context of an MCI, the most important distinction for in-hospital triage is between those who require immediate care and those who do not [6], [15], [13]. Aylwin et al. also argue for using two categories during on-site triage for those who require transport and those who do not [6].

A particularly controversial aspect of the medical response to an MCI, and by extension the triage process, involves how to deal with the expectant category. Outside the context of an MCI, every effort would be made to treat expectant patients in spite of the low probability that treatment will save their lives. However, in the aftermath of an MCI, and in keeping with the stated goal of doing the greatest good for the greatest number of people, Frykberg and others claim that patients in the expectant category should not be treated because critical resources can be better used on patients who are more likely to benefit from treatment [1], [9], [10], [13]. Even Hirshberg, who advocates giving severely wounded victims a level of care approximating the care they would receive under normal circumstances, acknowledges the need to focus treatment on patients that most likely to benefit from treatment [16]. Only Ashkenazi et al. refuse to accept an expectant category, and argue that it is unacceptable to deny these patients care just because their injuries occur during an MCI [5].

Of course, lost in the discussion of how to deal with victims in the expectant category is the need for effective tools to actually separate patients into these categories. Thoroughly reviewing the wealth of research in this area is outside the scope of this work, but some key findings are worth mentioning because of their ability to simplify and accelerate the triage process when faced with a large surge of MCTB victims. Meredith et al. suggest that simplified triage focusing on the ability to follow verbal commands is highly accurate in predicting which patients require urgent trauma care [21]. Other research finds that basing triage specifically on physiologic and anatomic indicators (ignoring mechanism of injury) significantly improves triage accuracy without adversely affecting outcomes [7]. In the specific context of a terrorist bombing, triage can capitalize on the distinct injury pattern associated with these incidents. Specific external signs have been shown to accurately predict two of the leading causes of critical mortality, suggesting that more efficient triage could be achieved after a terrorist bombing by focusing exclusively on external signs [2].

Some level of triage is always required at the scene of the incident to separate the immediate survivors from the dead, but after this initial assessment the remainder of the triage process focuses on classifying the survivors. Several studies argue that primary triage should occur on- or near-site followed by secondary triage at the entrance to the hospital [6], [9], [10], [13], [22]. Aschkenasy-Steuer et al. claim that pre-hospital triage cannot be trusted because not all wounded victims are transported to the hospital by emergency medical services (for instance, the walking wounded often take themselves to the hospital) [4]. Other authors argue that patients initially triaged as requiring delayed treatment be regularly reassessed after being admitted to lower-intensity areas of the ED in order to avoid triage errors [1], [3], [4], [16]. However, another recent study points to empirical evidence suggesting that severe injuries are not often missed during primary triage, which makes repeated triage an unnecessary use of valuable resources [5].

In a recent paper, Armstrong et al. admit that the question of "who should perform mass casualty triage across settings and how these multidisciplinary professionals should be trained as triage officers" is understudied and remains "ripe for investigation" [3]. Aylwin et al. report that on-scene triage performed by trained EMS was more accurate than that performed by ambulance services and medically-trained bystanders [6]. The conventional wisdom says that in-hospital triage should be performed by an experience trauma, emergency medicine, or general surgeon [1], [12], [13], [19], [22]. However, the results of a simulation model of the response to a terrorist bombing indicated that the accuracy of triage has little impact on outcomes, which suggests that triage need not be performed by the most experienced surgeons [14]. This view is echoed by Ashkenazi et al., who argue that because the most important asset for patient survival is an experience trauma surgeon, this individual should not be wasted on triage [5].

Behind each of these how, where, and who opinions on triage lies some understanding of the importance of triage accuracy. Armstrong et al. point out that triage is essentially a form of communication, and the lack of reliable communication is known to be a harbinger of poor outcomes in disaster management [3]. Triage accuracy is defined in terms of over-triage (classifying a non-severely wounded patient as severely wounded) and under-triage (classifying a severely wounded patient as non-severely wounded). Under-triage is clearly the more life-threatening of these two alternatives, and for this reason over-triage rates as high as 50 percent are often accepted as necessary during MCTBs to limit under-triage [7], [10], [19]. Several analyses by Frykberg and co-authors confirm this notion, finding that under-triage is usually negligible (less than 1 percent) while over-triage averages over 50 percent [9], [10], [13]. These same studies show that over-triage rates are positively correlated with critical mortality rates, suggesting that treating too many patients as severely wounded bogs down critical trauma resources. Contrasting these findings, Hirshberg et al. found in a simulation study that reducing the over-triage rate did not have a significant impact on outcomes [14]. Other authors similarly argue that the negative impact of triage errors can be mitigated by effective planning and flexibility. Another simulation study concluded that the ratio of critically injured to available treatment units affects critical mortality more than over-triage rates [18]. Aylwin et al. found that high over-triage was not associated with high critical mortality [6]. Over-triage can be compensated for by the use of improvised trauma beds, while the repeated reassessment of non-severely injured patients can catch victims with delayed presentation of severe wounds [5], [22].

Lastly, there is broad consensus that triage should be performed with a high degree of situational awareness. Almogy et al. suggest that rough information regarding the number of casualties and physical location of the incident should be communicated to the hospital as soon as possible, to which Armstrong et al. add that "the application of triage in mass casualties varies by casualty load and resource availability" [1], [3]. Acknowledging the controversy involved in not treating the expectant category, the bounds of this category should differ by incident type and location, and should be determined based on numbers and types of casualties and resource availability [3], [10], [13].

Delivery of Care

After victims have been triaged, effectively delivering the appropriate medical care requires detailed plans for the flow of each patient category through the ED or trauma center. Typically the treatment areas for those requiring immediate care is separated from the treatment area for those whose care can be delayed, and emphasis is placed on maintaining unidirectional patient flow [5], [10], [12], [14], [17]. In order to prepare the hospital for the expected influx of casualties, patients in the ED should be transferred to hospital floor beds, all nonurgent activity (including scheduled elective surgeries) should be halted, and available personnel should be summoned [1], [4]. Some initial estimate of the number and severity of expected casualties is critical at this stage, and it is important that management have the flexibility to transform other beds to trauma and ICU beds in order to handle the surge [1], [4], [6], [22]. However, Turégano et al. found that too many physicians, nurses, and students were called to the hospital, which crowded the ED, and that the decision to discharge all existing patients created more open beds than were actually needed [22]. This suggests that while flexibility is important, overcompensating for the expected surge can also be detrimental to the effective delivery of care.

Once patient flow has been determined and the appropriate resources have been mobilized, guidelines must be in place for assigning medical providers to treatment areas and for the standard of care that should be given. Several authors advocate assigning specifically designed treatment teams (for instance, one attending physician and two residents) to designated trauma rooms or groups of ED beds [1], [8], [10], [12]. Ashkenazi et al. suggest that expert trauma surgeons, ICU staff, and anesthesiologists not be assigned to specific sites, but rather be free to readily assist in the treatment of those who require expert care [5]. Multiple authors advocate for restricted radiology and laboratory testing and minimal blood bank usage while casualties are still arriving and the full scope of the incident is unknown [10], [12], [13], [14]. During this initial phase, surgery should be limited and should focus on damage control [1], [6], [12], [22]. In contrast, Ashkenazi et al. argue that after the severely wounded patients are identified, all needed resources should be allocated to their treatment and should not be delayed until the scope of the incident is known [5]. Finally, Hirshberg et al. advocate that non-critically wounded patients be treated using the principle of minimal acceptable care in order to preserve trauma resources [15].

Mathematical Modeling and Research Questions

The vast majority of the recommendations and opinions advocated in the papers referenced above are based on data analysis of past incidents and the personal experiences of the authors in

managing the medical response to MCIs and terrorist bombings. Mathematical modeling of the entire in-hospital response to a terrorist bombing (as opposed to just the triage process) is primarily limited to simulation studies, such as those by Hirshberg and his co-authors on resource utilization and the effect of casualty load on quality of care [14], [17]. In addition, Hupert et al. use simulation to analyze a range of scenarios and determine that the critical mortality is affected more by the ratio of critically injured patients to available treatment units than by overtriage [18]. However, these models do not resolve many of the questions raised above regarding the tradeoff between the different objectives, exactly how the triage process should be designed, how and where expert physicians and surgeons should be allocated, and what level of care should be delivered to victims.

Because the triage process is associated with the largest number of differing opinions, it is natural to focus on the impact of different triage systems on the two stated objectives of the medical response to a terrorist bombing MCI. Specifically, the goal of the proposed research is to use mathematical and simulation models to analyze an array of potential triage systems, and their impact on the rest of the trauma system, suggested by the varying opinions and positions put forth in the literature. The model will focus on testing different schemes related to the choice of triage categories, identifying the boundaries between categories, choosing who should perform triage, and triage efficiency and accuracy. The literature points to a tradeoff between the two competing objectives, and unlike existing mathematical models in this area, the proposed research aims to quantify this tradeoff and illuminate the impact of different triage schemes on the tradeoff. In keeping with the widely touted need for situation awareness, the model will be tested on a range of MCI scenarios in order to provide insight for emergency response planners into how the triage process and trauma system can be made to adapt to the needs of different incidents.

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