Case Study: Boston Bombings, a Surgeon's View

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Introduction

The injuries resulting from the two improvised explosive devices detonated on Boylston Street during the running of the 117th Boston Marathon at 14:49 on April 15, 2013, changed our lives forever. As a surgeon, soldier, Bostonian, 50+ time chronic marathoner, and participant in the 117th Boston Marathon (3:12 marathon, roughly an hour before the blasts), I will forever remember the events of that day and how they altered our city, and our country, in perpetuity. I remember those who died (29-year-old Krystle Campbell, 23-year-old Lu Lingzi, 8-year-old Martin Richard, and 27-year-old Sean Collier) and celebrate those who lived: the survivors. This chapter is dedicated to the survivors of the Boston Marathon bombing.

The Bombing

Two ground-level improvised explosive devices were detonated on Boylston Street during the running of the 117th Boston Marathon, at 14:49:43 and 14:49:57 on April 15, 2013. A total of 243 injured patients presented with a myriad of injuries (Fig. 37.1). Of the total population of 243 injured casualties, 152 patients presented to the emergency department (ED) within 24 hours of the explosions. Among the 152 patients presented within 24 hours, there were 66 patients who suffered from at

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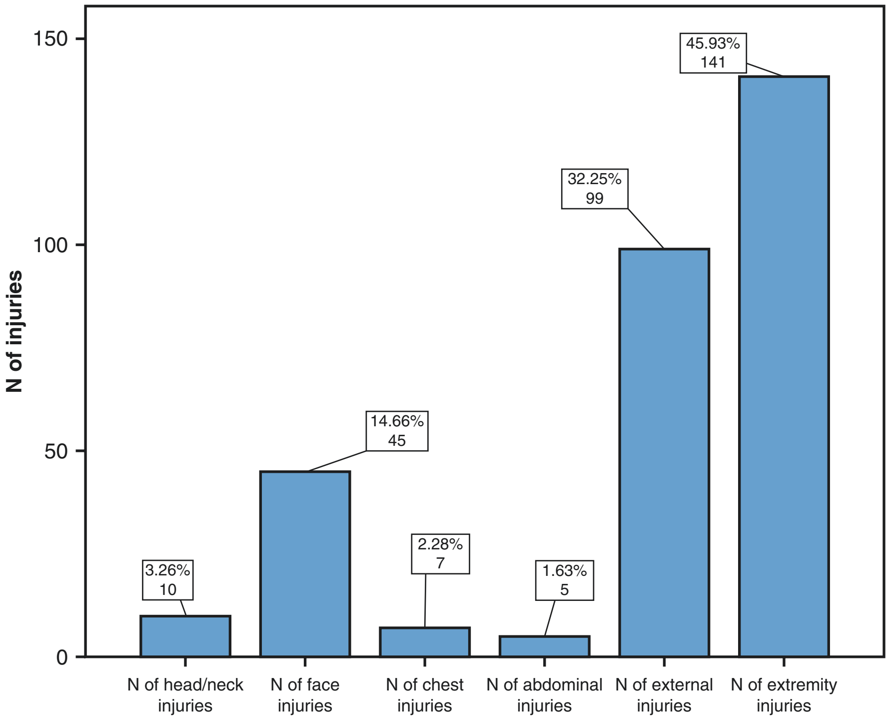


Fig. 37.1 Distribution of total injuries per body region among all 243 presenting patients

least one extremity injury. Figure 37.2 depicts the additional injury burden among all patients presenting with extremity injuries.

Of the 66 patients with extremity injury, 4 patients had upper extremities affected, 56 patients had only lower extremities affected, and 6 patients had combined upper and lower extremity injuries. There were 17 lower extremity traumatic amputations (LETA) in 15 patients, of whom 10 suffered below-knee traumatic amputation (BKA), 3 suffered above-knee traumatic amputation (AKA), 1 patient suffered bilateral BKA, and 1 suffered a BKA and an AKA.

There were additionally 10 patients with severe soft tissue injury (without traumatic amputation) having 12 lower extremities with 14 major vascular injuries (MVI). Seven of the latter were arterial (one femoral, two popliteal, and four other named arteries), and seven were venous (one femoral, three popliteal, and three other-named veins). Two lower extremities had combined arterial-venous injuries (one combined femoral arteriovenous and one combined popliteal arteriovenous injury). The burden of extremity injury is presented in Fig. 37.3.

Of all 66 patients with extremity injuries, 29 (44%) were recognized and documented as having life-threatening extremity exsanguination at the point of injury, including all 15 (100%) LETA patients, 7 of 10 (70%) MVI patients, and 7 of 41 (11%) non-LETA and non-MVI patients with other massive soft tissue and open long-bone fractures.

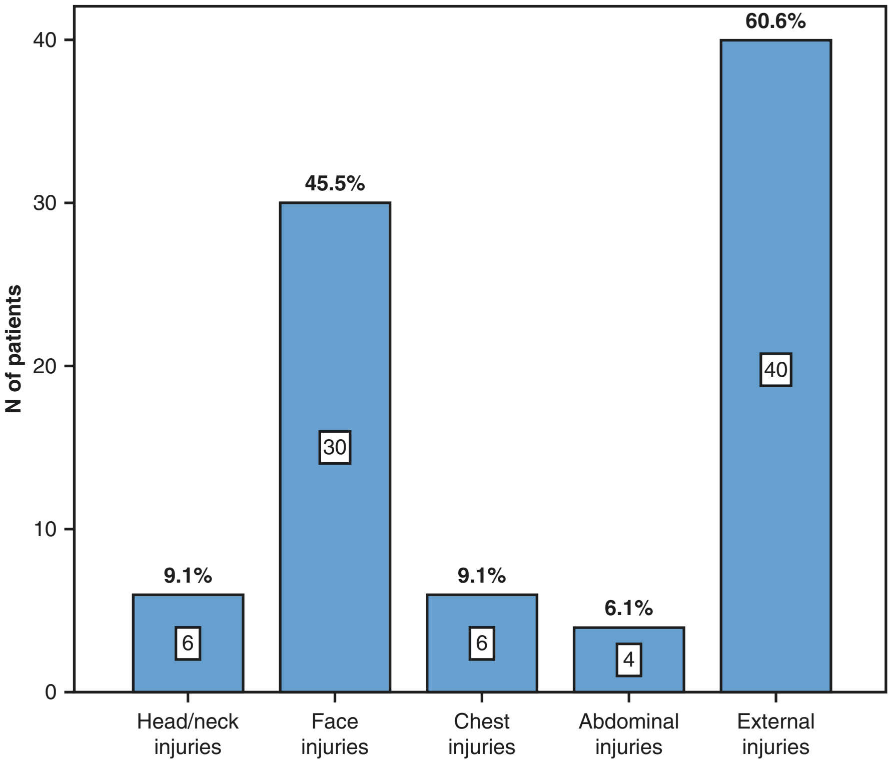


Fig. 37.2 Distribution of non-extremity injuries per body region among the 66 patients with extremity injuries

Among the 29 patients with recognized exsanguination, 27 tourniquets were applied at the point of injury: 94% of the LETA extremities, 42% of the lower extremities with major vascular injuries, and 6 of the 7 additional extremities with major soft tissue injury. No patient had more than one tourniquet per extremity, and no junctional injuries with significant hemorrhage were identified (although two patients who died on the scene had severe junctional injuries). Of the 16 LETA patients with tourniquets, 4 had improvised tourniquets applied by EMS, 7 had improvised tourniquets applied by non-EMS responders (some of whom had known medical training but were not acting as part of the official EMS response, including physicians, off-duty soldiers, etc.), and 5 had improvised tourniquets of unknown origin. Of the five lower extremities with MVI, two had improvised tourniquets applied by EMS, two had improvised tourniquets applied by non-EMS responders, and one had an improvised tourniquet of unknown origin. Of the six additional extremities with major soft tissue injury and exsanguination, four had improvised tourniquets applied by EMS, and two had improvised tourniquets of unknown origin. Figures 37.4 and 37.5 reflect the sources of the tourniquets recovered. In total, 37% of tourniquets were applied by EMS. Eight

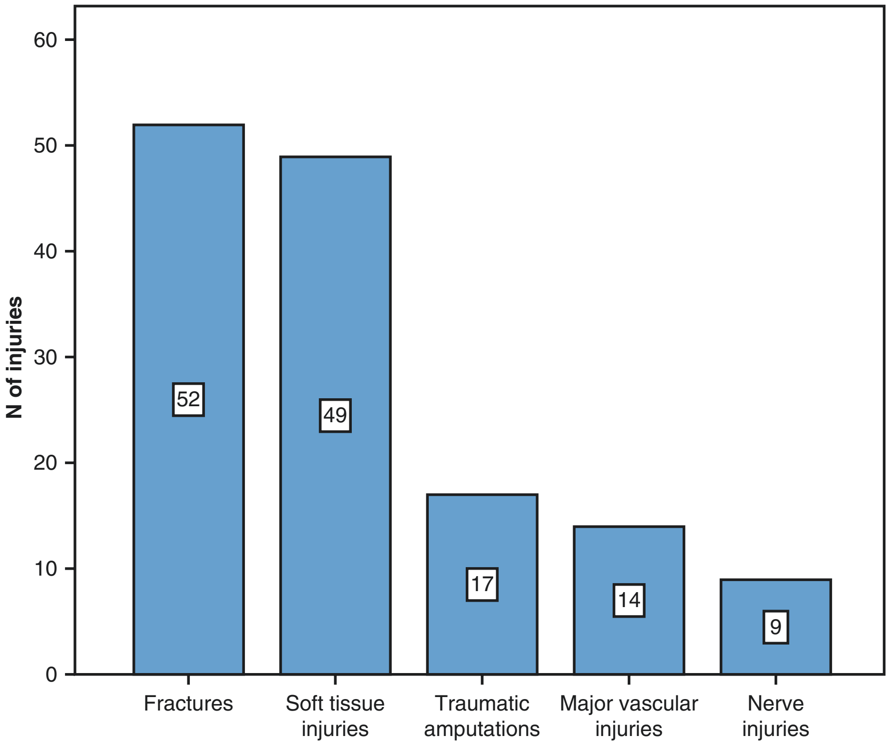
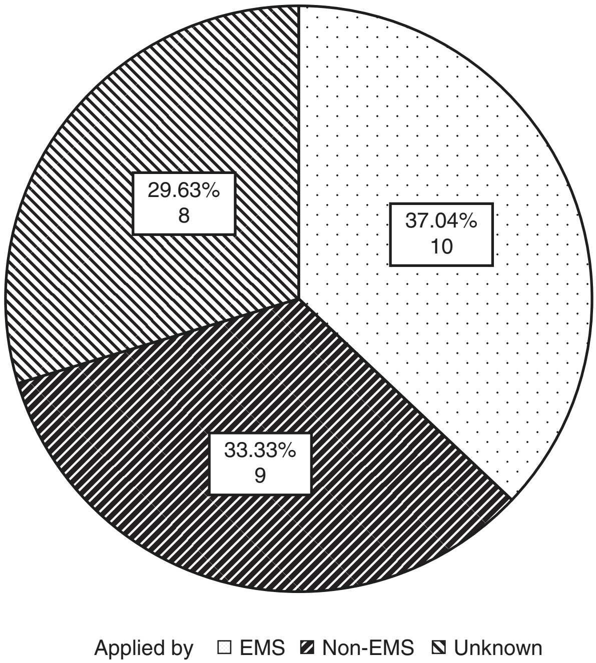


Fig. 37.3 Distribution of extremity injuries by type among the 66 patients with injured limbs

Fig. 37.4 Sources of the 27 tourniquets



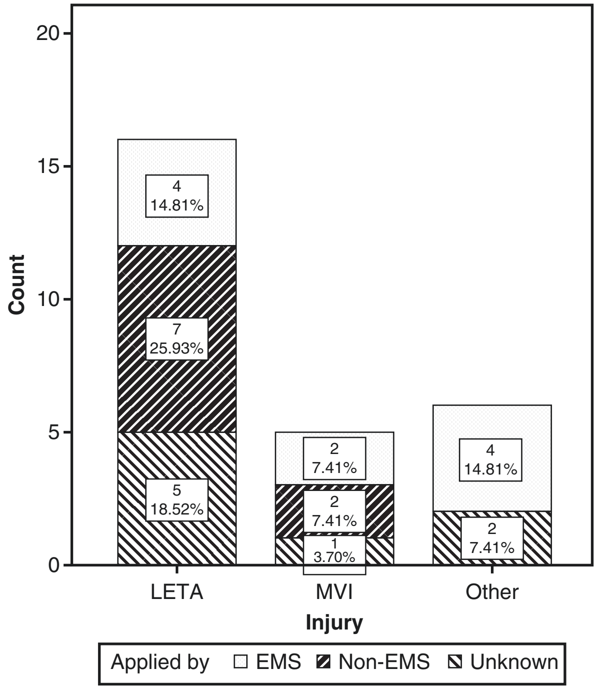


Fig. 37.5 Sources of the 27 tourniquets among 66 patients with extremity injury categorized by injury type

limbs presented to the ED with life-threatening exsanguination and had no pre-hospital tourniquet in place on arrival.

All tourniquets were improvised, including those applied by EMS, and no commercially available and purpose-designed tourniquets were identified. A review of photography and video from the scene response demonstrates a single extremity with soft tissue injury (but not a LETA) identified with a Combat Application Tourniquet (CAT) in place. We have no knowledge of this patient's trauma burden or outcome. At the Massachusetts General Hospital, all six improvised tourniquets encountered were venous tourniquets and required replacement with a commercial tourniquet to prevent ongoing extremity exsanguination. Similar reports exist from other Boston hospitals. Among the 66 patients with extremity injuries, mortality was 0%.

Triage and Index Surgery

Patients were repeatedly triaged, first at the point of injury, then at the EMS staging area near the bombing, then on the ambulance ramps of our hospital, and finally again in each of our trauma resuscitation rooms. Triage decisions are imperfect, by their very nature, and frequent re-evaluation allows for an opportunity to identify developing changes in conditions that will alter triage decisions. The decision to move a patient to the operating room is binary and generally irreversible, which commits those resources to that patient until the operation is done. Consequently, repeated preoperative triage is necessary to ensure that only the sickest patient (who have salvageable injuries) make it to the operating room. Importantly, patients with isolated limb injuries who have effective hemostasis with well-placed tourniquets do not need emergent surgery for their limb injuries. Caution is necessary, however, since these patients often have coexisting torso injuries that may be overlooked due to the visually stimulating (and distracting) extremity injuries. Attention should be directed to cavitary triage of the torso, not the striking limb injury with an effective tourniquet in place.

Analysis of the Unthinkable

Although the Boston Marathon bombing was not the first terrorist event in the United States, it was the first modern event to create mass casualties with a pattern of severe lower extremity blast injury commonly seen on the battlefield from improvised explosive devices [9]. The Boston experience demonstrated the nearly universal use of improvised tourniquets as a primary prehospital and presurgical attempt at hemostatic intervention for life-threatening extremity hemorrhage: an attempt at damage control that largely failed. A recent study conducted in Boston describes the city's informal tourniquet protocol and use of the commonly seen improvised tourniquet after the bombing. This manuscript, however, conspicuously omits data regarding effectiveness of the improvised tourniquet or why this device was specifically selected over others [12]. Recent data derived from military experience does not support the use of improvised tourniquets as best practice, as multiple studies [3–8] have consistently reported superior hemostatic results with the use of commercial, purpose-designed tourniquets. Our collective military experience has also established the hemostatic superiority of the commercially available devices by directly comparing them to improvised devices [13–15]. As a result, US combat personnel are now trained in self- and buddy application of these purpose-designed tourniquets [1, 3–8], and each US military service member carries at least one commercial tourniquet (often two). The translation of this military posture (general availability of tourniquets and widespread training on how to apply them correctly) to the homeland has not been maximally realized, unlike other battlefield lessons such as early use of antifibrinolytics, high-ratio transfusion, and abbreviated surgery, which have gained far more translational traction [16]. Had translation been more successful, one may have expected far more than a single commercial tourniquet identified after the bombing. Hemorrhage control is the first step of damage control, and damage control must start at the point of wounding.

Additional evidence from the civilian community [15, 17] demonstrates an obvious deficiency in the translation of the military's extremity hemorrhage control posture. A retrospective study on trauma registries at two large level 1 trauma centers in Canada [15] revealed that of 190 patients who suffered isolated extremity injuries with arterial injury, only 4 patients had a tourniquet present upon arrival. Those were all improvised tourniquets (neck tie, belt, or handkerchief) applied by police or bystanders. In the non-tourniquet group, six deaths were recorded as a direct result of exsanguination. While statistically significant differences were difficult to observe given the small number of patients who received a prehospital tourniquet, this study highlights the profound absence of systematic use of tourniquets in the prehospital environment. Following this, the 2012 Adult Traumatic Hemorrhage Control Protocol was introduced to all EMS providers in the province of Alberta, Canada – a protocol that advises the use of a commercial tourniquet for uncontrolled extremity bleeding and completes the translation of battlefield lessons to the homeland. Each state in the United States should consider adopting a similar protocol.

Although it is certainly possible to improvise an effective arterial tourniquet, the data suggests this is uncommonly done appropriately, especially under stress [4, 10–17]. An improvised tourniquet should (1) be wide enough to compress arterial and venous vasculature without creating pressure necrosis of the skin or neuropraxia (as may occur with narrow tourniquets, such as rubber tubing) and (2) have a device attached to create a mechanical advantage to generate adequate circumferential pressure (such as a windlass). The improvised tourniquets used in Boston met only the second of these two fundamental criteria. It is important to note that as materials science and tourniquet technology advances, it may be possible to create an effective arterial tourniquet device without a windlass [18, 19].

While full translation of the military posture regarding extremity hemorrhage control and tourniquet use may be ideal, one must accept that, in the setting of sudden disaster, tourniquets will continue to be improvised despite all efforts at translation by policy-makers. It is clear that improvised tourniquets, and the temporary hemorrhage control they offer, will always be used in mass casualty scenarios, and their role should not be entirely discounted. An improvised venous tourniquet can provide temporary hemorrhage control [3, 5, 6]; however, a comprehensive review of emergency tourniquet use recently highlighted the significance of unintentional venous tourniquets as potentially deadly [2], particularly in the minutes following initial bleeding control. The experience in Boston, with apparent, initial, hemostasis with improvised tourniquets at point of injury, supports this notion and appears to echo that of known paradoxical bleeding after venous tourniquet application. Venous tourniquets can create initial adequate hemorrhage control that soon worsens, as a time-dependent function, until hemorrhage control is lost and supplanted by paradoxical hemorrhage, the worsening of hemorrhage than if no tourniquet were used at all [3]. Perhaps an educational campaign to teach the correct way to apply a purpose-designed tourniquet, as well as how to improvise an effective arterial tourniquet, may be appropriate since it is nearly certain that limbs will have improvised tourniquets applied after the next, unfortunate, bombing in the homeland. Several studies suggest that adequate training can be minimal (less than a minute) and still result in trainees who can apply effective tourniquets [18, 19].

Despite some possible limitations with respect to prehospital extremity hemorrhage control, there were no inhospital deaths. The mean transport time from point of injury to ED was 24 min, substantially faster than the range of commonly reported evacuation times in the military and civilian literature, which could vary from well under 1 hour to over 2 hours after time of wounding, depending on the setting and circumstances [10, 13, 20–23]. The high number of Boston area metropolitan trauma centers all co-located in a very small geographic area in close proximity to the Boston Marathon finish line likely contributed to this rapid evacuation time, as well as the robust medical infrastructure already in place at the finish line for the expected event-related illnesses.

The Boston bombing experience suggests that (1) instances of multiple exsanguinating extremity injuries, similar to battlefield wounds, can occur in the homeland and (2) improvised tourniquets likely provided initial hemorrhage control, but the absence of purpose-designed devices in the bombing response probably created some cases of paradoxical bleeding. When contrasted to the wealth of evidence gathered from the last decade of military experience, these findings call for a reconsideration of our practices. We recommend that all EMS services translate a military posture with an extremity hemorrhage control protocol that emphasizes appropriate training with liberal availability of commercial, purpose-designed tourniquets. Proper tourniquet application techniques should be presented in the Advanced Trauma Life Support and Prehospital Trauma Life Support training manuals, among others. Several notable organizations, including the Hartford Consensus and the American College of Surgeons, are recommending translation and adoption of military posture toward prehospital extremity hemorrhage control [24, 25]. Physician leaders and policy-makers should insist on translation of a prehospital extremity hemorrhage control posture similar to the ubiquitous adoption and presence of automated external defibrillators in nearly every ambulance, federal building, cafeteria, and other public gathering area in the United States.

Lessons Learned

Although much attention has been given to the obvious absence of purpose-made tourniquets in the Boston bombing response, other lessons were also learned of significant importance. For the sake of completeness, the entire list of lessons learned is presented here.

- *Tourniquets work, are safe, require training, and need to be ubiquitous*. No purpose-designed tourniquets or advanced topical hemostatic agents were available. Although we must not discourage bystanders from responding to disaster to aid the injured, we must also be intellectually honest and recognize that (despite the lay press reporting) the improvised tourniquets applied on Boylston were likely not arterial tourniquets. Improvisation of an arterial tourniquet is a skill set that can be taught and should be widely incorporated into general first aid classes. If purpose-made tourniquets had been available, proper training to ensure correct application is necessary. The Committee for Tactical Emergency Casualty Care (C-TECC) and the Committee on Tactical Combat Casualty Care (CoTCCC) published guidelines regarding tourniquet use and formal training, and written protocols are widely available. These should be adopted as permanent part of the curriculum for every first responder.

- *There was too much "stay and play" in the medical tent at the finish line*. While the finish line medical tent instantly became the de facto triage area after the bombing, the transport time recorded for many severely injured patients was over an hour. Either by design or by a matter of mass confusion, some patients remained in the medical tent for an extended period. In a city with five level 1 trauma centers and hundreds of patients with surgical injuries, patients should be moved to hospitals in a swifter fashion.
- *Triage is dynamic*. Triage must be rapid and medical providers must accept that the triage process will be imperfect. Patients who are triaged as emergent may, in fact, not be dying. Other patients triaged as non-emergent may unexpectedly deteriorate. Frequent re-triage is required and may alter initial triage decisions. In the emergency department, patients should be re-triaged by a senior surgeon or senior emergency medicine physician. Utilization of the operating rooms is a finite resource, and only patients who truly need a life-saving operation should be triaged straight to the operating room. Care decisions should be made regarding axial imaging studies as many of these studies are initially unnecessary. A plain chest X-ray and a focused abdominal ultrasound exam are often the only imaging required to make informed inhospital triage decisions.
- *The most visually stimulating injury is often not the most life-threatening one.* The Boston bombing patients arrived with extremely devastating, and visually stimulating, limb injuries. These injuries, despite their appearance, were easily controlled with tourniquets. Some patients also had coexisting intracavitary hemorrhage. This can often be overlooked when the clinician inappropriately focused on the limb injury and neglects a complete trauma evaluation, particularly of the peritoneal and thoracic cavities. Once an effective tourniquet is in place, the limb injury becomes (temporarily) forgettable.
- *Damage control starts at the point of injury*. The damage control resuscitation (DCR) principles begin at point of injury, must be maintained during patient transportation, and should be aggressively implemented in the ED in order to prepare patients for best surgical survival. A low volume (or no volume) crystalloid fluid restrictive resuscitation strategy should be adopted. Patients waiting for less-than-emergent surgery should receive minimal crystalloid therapy. If resuscitation is required, volume expansion with a transfusion strategy that approximates fresh whole blood should be utilized. For many hospitals, this means adopting a strategy of high-ratio transfusion of packed red blood cells:plasma:platelets. All fluids and blood products should be warmed to normal body temperature. Antifibrinolytics should be liberally administered. For patients with limb injuries that have a tourniquet in place and are waiting for surgery, tourniquet conversion should be considered if time and manpower permit.
- *Damage control surgery is vital.* In the operating room, only hemorrhage control and contamination control are desired. Abbreviated surgery, vascular shunts, bowel stapled and left in discontinuity, and temporary abdominal closures should dominate the landscape. Ideally, only warmed blood and blood products should

be administered during damage control surgery. The operating room should be made as warm as possible; the surgeon should become exceedingly uncomfortable with the temperature in the room. When in doubt, all body cavities should be surgically interrogated. Bilateral tube thoracostomy, pericardial window, and laparotomy are the imaging methods of choice during damage control in disasters. Patients should be rapidly transferred to the intensive care unit and the operating room reset for the next patient. Once all index operations are complete, the entire team should reassemble to re-triage and regroup resources.

- *Sequential medical record numbers are dangerous.* Assigning patients sequential medical record numbers in simple escalating numerical fashion creates an unacceptable margin of error since there will be many simultaneous patients with medical record numbers differing by only a single digit (1,234,567, 1,234,568, 1,234,569…). This creates an unacceptable environment for a potential clerical error, single keystroke mistake, that would potentially result in a surgeon looking at the hemoglobin value of the wrong patient or (worse yet) ordering tests or procedures on the wrong patient. Medical record numbers during disasters should vary widely to prevent this error.
- *Don't go home just yet: the tertiary trauma survey is extremely important*. In disasters, it is a common urge to "take a break" once each patient's index operation is complete and all the bleeding and contamination are controlled. This, however, is a mistake. Once the initial surgery is done, the entire trauma team should reassemble to go over each patient again, in extreme detail. The purpose of this is twofold. First, the entire team needs to understand each patient's condition and status, so appropriate planning for operative take-backs, additional imaging, and other interventions can be planned and prioritized. Second, small injuries are commonly missed and will only be identified by a careful tertiary survey. Although most of our patients had non-life-threatening ruptured tympanic membranes, for example, these were largely not identified until posttrauma day 2 on a careful tertiary exam. This is, of course, an appropriate injury to miss on initial evaluation in a mass casualty situation; however, failure to recognize and treat this injury (and others like it) could result in long-term disability.
- *Human resource management is critical.* If the disaster is expected to become protracted, rest and sleep cycles should be mandated so that human resources do not become all simultaneously exhausted. Responders will not go home or rest voluntarily; this becomes a leadership imperative.

Conclusion

The Boston Marathon bombing solidified multiple lessons for our city. First, damage control starts at the point of injury. No one should die from a preventable cause of death such as limb exsanguination. The prehospital response to extremity exsanguination after the Boston Marathon bombing demonstrates that our current practice is an approach, lost in translation, from the battlefield to the homeland. Proper tourniquet application techniques should be presented in the Advanced Trauma Life Support and Prehospital Trauma Life Support training manuals, among others. Second, triage becomes the most important decision that is made on the scene of a disaster. That decision should be revisited often following initial triage of all casualties. Third, re-triage at the hospital is important to prevent inappropriate utilization of human and physical plant infrastructure on patients who are not truly dying. Finally, abbreviated surgery with attention to high-ratio transfusion, use of antifibrinolytics, vascular shunts, contamination control, and temporary abdominal (or chest) closure is necessary.

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