Outcomes of IED Foot and Ankle Blast Injuries

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Background: Improvements in protection and medical treatments have resulted in increasing numbers of modern-warfare casualties surviving with complex lower-extremity injuries. To our knowledge, there has been no prior analysis of foot and ankle blast injuries as a result of improvised explosive devices (IEDs). The aims of this study were to report the pattern of injury and determine which factors are associated with a poor clinical outcome.

Methods: U.K. service personnel who had sustained lower leg injuries following an under-vehicle explosion from January 2006 to December 2008 were identified with the use of a prospective trauma registry. Patient demographics, injury severity, the nature of the lower leg injury, and the type of clinical management were recorded. Clinical end points were determined by (1) the need for amputation and (2) ongoing clinical symptoms.

Results: Sixty-three U.K. service personnel (eighty-nine injured limbs) with lower leg injuries from an explosion were identified. Fifty-one percent of the casualties sustained multisegmental injuries to the foot and ankle. Twenty-six legs (29%) required amputation, with six of them amputated because of chronic pain eighteen months following injury. Regression analysis revealed that hindfoot injuries, open fractures, and vascular injuries were independent predictors of amputation. At the time of final follow-up, sixty-six (74%) of the injured limbs had persisting symptoms related to the injury, and only nine (14%) of the service members were fit to return to their preinjury duties.

Conclusions: This study demonstrates that foot and ankle injuries from IEDs are associated with a high amputation rate and frequently with a poor clinical outcome. Although not life-threatening, they remain a source of long-term morbidity in an active population.

Level of Evidence: Therapeutic Level IV. See Instructions for Authors for a complete description of levels of evidence.

The conflicts in Iraq and Afghanistan have seen the emergence of the improvised explosive device (IED) and anti-vehicle mines as the signature weapon of the insurgents. These weapons, capable of causing multiple injuries in a single incident, pose a substantial threat to coalition troops in those regions. Improvements in protection have resulted in increasing numbers of casualties surviving with complex extremity injuries, often with long-term disability. Understanding the mechanism and pattern of the injuries inflicted by these devices can provide a focus for future research into blast mitigation and clinical management.

Blast injury is the generic term for the various effects of an explosion on the human body. By convention, blast injuries are classified according to the mechanism by which they are produced. Primary blast injury results from the interaction of the blast wave with the body. Injury is largely confined to air-containing organs such as the lungs and bowel. Secondary blast injury is related to penetrating trauma from bomb fragments or debris. Tertiary blast injury is caused by the effects of bodily displacement of casualties by the blast wind, and quaternary blast effects are related to thermal and inhalational injuries as a result of the explosion (Fig. 1).

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Modes of injury from explosions.

Although these injury mechanisms can be differentiated relatively easily when they are the result of open free-field explosions (i.e., above-the-ground detonations in a clear environment), their interaction with the body is more complex in other environments. The relative effect of each blast injury mechanism is determined by the nature of the explosive and the environment in which the explosion occurs.

In an attempt to differentiate between the effects of different environments on the pattern of blast injury, Draeger et al. developed the concept of solid blast to denote the material medium that harmfully transmits the explosive force. Solid blast refers to the detonation of an explosive in the proximity of a semirigid body, such as a ship. This results in the transmission of energy through the solid structure, causing a sudden acceleration of surfaces. Since these injuries are predominantly caused by rapid deck deflection, the damage is greatest to the lower extremities. In a review of fifty casualties injured in a ship explosion, Barr et al. reported that 36% sustained open fractures of the calcaneus, talus, and distal part of the tibia. They noted that the pattern of injury in this group of patients differed from those of individuals caught in an air or water blast in that primary and secondary blast injuries were rarely seen. This is very similar to the findings in our previously published forensic biomechanical review of extremity injuries in explosions. We reported that 94% of the injuries sustained in an enclosed environment were attributable to tertiary blast effects.

Although ship explosions have been relatively uncommon in the past sixty years, a similar explosive mechanism is seen in anti-vehicle mine blasts. When an anti-vehicle mine detonates, the blast wave from the explosion causes the release of a cone of superheated gas and soil that impacts the underside of the travelling vehicle. This leads to rapid deflection of the vehicle floor, transmitting a very-short-duration (typically 5-ms), high-amplitude load into the foot and ankle.

It has been demonstrated that patients with foot and ankle injuries have significantly greater disability scores than those without foot and ankle injuries. These effects may be even more pronounced in a young military population, who have a high functional demand.

To our knowledge, clinical information related to under-vehicle mine incidents has been limited to a single case series of injuries over a five-year period in Croatia. The dearth of clinical information related to this injury pattern, the aims of this study were to document the pattern and clinical outcomes of lower leg injuries from under-vehicle explosions with utilization of contemporary battlefield injury data, and to analyze these data to determine whether specific elements of the injury complex are associated with a poor clinical outcome.

Materials and Methods

A retrospective study was conducted with use of a prospectively collected combat trauma registry (Joint Theatre Trauma Registry [JTTR])17. This study was granted approval by the local clinical governance and audit board (CA-1-01946-08). The JTTR was used to identify all U.K. service personnel who had sustained lower leg injuries from an explosive injury mechanism from January 2006 to December 2008. From this initial data capture, casualties who had sustained a lower leg injury from a vehicle explosion were selected for further study and cross-referenced with incident data to confirm the mechanism of injury. The prehospital medical documentation, field hospital management, trauma radiographs, U.K. hospital notes, and rehabilitation documentation were reviewed. Traumatic amputations were excluded from the study.

Demographic data, the New Injury Severity Score (NISS), and all associated injuries were recorded for each patient. The foot and ankle injuries were categorized on the basis of the anatomical segment injured: (1) forefoot, (2) midfoot, (3) hindfoot, or (4) tibia. The severity of each foot and ankle injury was evaluated with use of the Foot and Ankle Severity Scale (FASS). The FASS assigns a severity level to ninety-one separate foot and ankle traumatic injuries on a scale of 1 to 6, with 6 considered currently untreatable.

Fractures within the foot and ankle complex were categorized as either closed or open. Open fractures were subcategorized with use of the classification system of Gustilo et al.23. As all were high-energy explosive injuries, they fell into one of two groups: grade IIIA+B (open fractures with no vascular injury) or grade IIIC (open fractures with an associated vascular injury).

The development of wound infection, osteomyelitis, traumatic osteoarthritis, and the need for amputation was recorded for each injury. The timing of amputation was categorized into three groups: (1) primary amputation at the field hospital, (2) delayed primary amputation following evacuation to the U.K., and (3) secondary amputation following discharge from the acute surgical care unit. In addition, the type of surgical management, including the method of fixation and the method of soft-tissue reconstruction, was noted.

Limb-specific clinical end points were determined by the need for amputation and by ongoing clinical symptoms. The clinical result was considered to be poor when, at the time of final review, the limb continued to require substantial medical intervention because of (1) persistent chronic infection (defined as either osteomyelitis or persistent wound infection twelve months postinjury), (2) delayed fracture-healing (more than twelve months postinjury), or (3) symptomatic posttraumatic osteoarthritis. Limbs that were surgically amputated were also considered to have a poor clinical result.

Overall functional outcome was determined by the ability of the patient to return to military duty. On the basis of standardized military employment criteria, one of four employment categories (full military duty, limited duty, sedentary duty only, and unfit for military duty) was assigned. The assignment of the employment category is independent of the service members’ role within the military. To be fully fit to return to military duty, they must be able to pass standardized fitness tests involving running and marching. Those categorized as “limited duty” are not considered fit to operate in forward operating areas, and those who are fit for sedentary duty only are considered unfit to deploy outside a home base.
Source of Funding
No funding was received for this study.

Statistical Methods
Statistical analysis was performed with use of PASW v18.0 software (IBM, Armonk, New York). The chi-square test was used to analyze categorical data. A binomial logistic regression analysis was performed to explore the relationship between the injury profile and amputation. Amputations in the field hospital are performed only when there is a substantial risk to life, or if the limb is so badly damaged that limb salvage is not an option. Hence, limbs that were primarily amputated were excluded from the statistical model.

Results Patient Demographics
From January 2006 to December 2008, sixty-three casualties sustained a total of eighty-nine foot and ankle injuries (twenty-six bilateral injuries) in vehicle explosions. The mean age of the military personnel was twenty-six years (standard deviation [s.d.] = 5.75 years). The mean duration of follow-up was 33.3 months (s.d. = 10.8 months). The median NISS score was 16 points (range, 4 to 75 points), with the most severely injured body region being the lower extremity in 89% of the cases, the spine in 5%, and the head and chest in 3% each. Twenty-two casualties (35%) had isolated injuries to the lower leg. The pattern of associated injuries is shown in Figure 2.

Foot and Ankle Injuries
The relative frequency of anatomical foot and ankle segments injured is represented in the Appendix, with injuries to the hindfoot and distal part of the tibia more common than injuries to the forefoot and midfoot. Fifty-one percent of the injured lower limbs had sustained multisegmental injuries (see Appendix).

The median FASS score for injury severity was 4.0, with 70% of the injuries classified as severe or worse (an FASS score of ≥4). The distribution of FASS scores is shown in the Appendix.

Of the eighty-nine limb injuries, six (7%) involved the soft tissue only, thirty-eight (43%) were closed fractures, twenty-eight (31%) were open fractures with no vascular injury (Gustilo grade IIIA+B), and seventeen (19%) were open fractures with vascular involvement (Gustilo grade IIIC).

Clinical Management
All casualties were transferred to the field hospital from the point of injury via helicopter. The median time from the point of injury to arrival at the field hospital was 1.6 hours. On arrival at the hospital, eleven limbs had a tourniquet already applied (mean tourniquet application time, ninety-four minutes [s.d. = 58.1 minutes]). In line with standard U.K. military surgical practice, internal fixation was not performed at the time of the initial surgery. Forty-four limbs were treated with plaster-cast stabilization, twenty-three were treated with external fixation, and eight were treated with surgical debridement alone. Fasciotomies were performed because of developing or impending compartment syndrome in twenty-four limbs (27%); there were eleven fasciotomies of the lower leg, eight of the foot, and five of both the foot and the lower leg. Following fasciotomy, negative pressure wound therapy was applied to the limb segment to reduce the need for elevation. Thirteen limbs were considered unsalvageable and were amputated primarily at the field hospital; all had sustained Gustilo grade IIIC injuries.

TABLE I Complications Following Foot and Ankle Blast Injuries*

<table>
<thead>
<tr>
<th>Injury</th>
<th>Total</th>
<th>Primary Amputation</th>
<th>Salvaged</th>
<th>Infection</th>
<th>Osteomyelitis</th>
<th>Traumatic Osteoarthritis</th>
<th>Nonunion</th>
<th>Total Amputations</th>
<th>Ongoing Symptoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>No fracture</td>
<td>6</td>
<td>0</td>
<td>6 (100)</td>
<td>2 (33)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>3 (50)</td>
</tr>
<tr>
<td>Fracture</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Closed</td>
<td>38</td>
<td>0</td>
<td>38 (100)</td>
<td>7 (18)</td>
<td>0 (0)</td>
<td>17 (45)</td>
<td>7 (18)</td>
<td>2 (5)</td>
<td>24 (63)</td>
</tr>
<tr>
<td>IIIA+IIIB</td>
<td>28</td>
<td>0</td>
<td>28 (100)</td>
<td>18 (64)</td>
<td>7 (25)</td>
<td>5 (18)</td>
<td>7 (25)</td>
<td>8 (29)</td>
<td>22 (79)</td>
</tr>
<tr>
<td>IIIC</td>
<td>17</td>
<td>13</td>
<td>4 (24)</td>
<td>2 (50)</td>
<td>1 (25)</td>
<td>1 (25)</td>
<td>1 (25)</td>
<td>16 (94)</td>
<td>17 (100)</td>
</tr>
</tbody>
</table>

*The values are given as the number with the percentage in parentheses.
Following the initial surgery in the field hospital, all casualties were evacuated to the Royal Centre for Defence Medicine (Selly Oak Hospital, Birmingham, United Kingdom) for further medical treatment. Of the seventy-six salvaged limbs, thirty underwent fracture stabilization with plate fixation or percutaneous screw fixation, ten underwent intramedullary nailing, twelve had plaster-cast immobilization, and two were treated definitively with an external fixator or circular frame. Delayed primary wound closure was achieved in nine cases (12%), twenty-seven limbs (36%) required split-thickness skin-grafting, and six (8%) required local or free tissue transfers. Seven limbs were considered unsalvageable on return to the Royal Centre for Defence Medicine, once the zone of injury had been fully delineated, and required a delayed primary amputation, all within the first week after hospital admission.

The local complications following injury are shown in Table I. The remaining sixty-nine salvaged limbs had an overall infection rate of 42% (twenty-nine limbs) and an osteomyelitis rate of 12% (eight limbs). Nonunion was noted in 22% (fifteen), and traumatic osteoarthritis was seen in 33% (twenty-three) of the sixty-nine salvaged limbs. Because of the level of soft-tissue injury in these cases, no feet underwent primary fusion on return to the U.K.; however, eight (12%) subsequently required fusion during the study period.

Twenty-six (29%) of the injured limbs were amputated. Six were amputated as a secondary procedure because of chronic pain at a mean of 18.5 months postinjury. The overall outcomes are presented in Figure 3.

A binomial logistic regression model was developed to probe the relationship between the pattern of injury and the

### Table II Results of Binomial Logistic Regression Model for Amputation*

<table>
<thead>
<tr>
<th>Variable</th>
<th>Logit Coefficient, β</th>
<th>Odds Ratio (95% Confidence Interval)</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>NS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NISS score</td>
<td>NS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tourniquet</td>
<td>NS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vascular injury</td>
<td>-3.43</td>
<td>0.03 (0.001-0.24)</td>
<td>0.04</td>
</tr>
<tr>
<td>Open fracture</td>
<td>-2.16</td>
<td>0.11 (0.01-1.037)</td>
<td>0.03</td>
</tr>
<tr>
<td>≥2 foot and ankle segments injured</td>
<td>NS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forefoot injury</td>
<td>-1.89</td>
<td>0.15 (0.01-0.77)</td>
<td>0.031</td>
</tr>
<tr>
<td>Midfoot injury</td>
<td>NS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hindfoot injury</td>
<td>-3.13</td>
<td>0.05 (0.01-2.01)</td>
<td>0.014</td>
</tr>
<tr>
<td>Tibial injury</td>
<td>NS</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*R² coefficient = 0.58. NS = not significant.
Protection and vehicle design in modern warfare is related to improvements in personal protective measures to reduce long-term disability. These improvements have led to increased survivability from this injury mechanism by protecting the vehicle occupants from the close proximity of the explosion. The net result of these effects is more survivors with complex lower-limb injuries. This was demonstrated in our study, in which 70% of the injured lower limbs had a FASS score of ≥4 (representative of a substantial injury).

In addition to the foot and ankle injury, 65% of the casualties in our series sustained injuries to other body regions, with spinal injuries recorded in 22%. The association between lower-limb injuries and spinal fractures was also noted by Covey et al. in a study of forty-one patients with musculoskeletal blast injuries at a U.S. military field hospital during the Yugoslav War; they reported three cases of spinal fractures in vehicle-borne troops. The level of polytrauma in these casualties is reflected by the high median NISS score in our study. Combined with the severity of the lower leg injury, this demonstrates the high-energy injury mechanism seen in under-vehicle explosions. The substantial bone and soft-tissue injury caused by solid blasts often results in a limb that is not amenable to surgical reconstruction; amputation is often the only medical option. Our multinomial regression analysis showed open fractures, hindfoot injuries, and vascular insults to be associated with an increased risk of amputation. We previously reported that a calcaneal fracture was associated with a 45% amputation rate, with only 6% of casualties able to return to full military duty following injury.

Despite the development of standardized protocols of systematic soft-tissue debridement, early targeted antimicrobial therapy, use of topical negative pressure therapy dressings for exudate control, and early soft-tissue coverage where possible, the rate of infection in the salvaged limbs was 42%. This is greater than the infection rates in studies of complex foot trauma in civilians, which have been reported to be between 7.1% and 22.2%. Our increased infection rate is related to the significantly greater soft-tissue injury and contamination found in military injury patterns.

The severity of injuries resulting from explosions is reflected in the high percentage of limbs that had a poor clinical outcome. At a mean of 33.3 months postinjury, 74% of the limbs injured required ongoing medical care, with only nine (14%) of the individuals able to return to their preinjury occupational roles. Forty-one (65%) were fit for only sedentary duties or deemed unfit for any military service.

**Discussion**

The foot and ankle injuries described in our study are similar to those from ship-borne explosions in World War II. As previously reported, injuries to the hindfoot and distal part of the tibia were frequent, with multisegmental injuries a common finding. This has been corroborated in our study, in which >50% of the casualties had injuries to more than one foot and ankle segment. We believe that this “solid blast” injury in modern warfare is related to improvements in personal protection and vehicle design. These improvements have led to increased survivability from this injury mechanism by protecting the vehicle occupants from the close proximity of the explosion. The net result of these effects is more survivors with complex lower-limb injuries. This was demonstrated in our study, in which 70% of the injured lower limbs had a FASS score of ≥4 (representative of a substantial injury).

In this series, we automatically assigned limbs requiring amputation into the poor clinical outcome group. It is conceivable that patients who had an amputation had better clinical outcomes compared with the limb reconstruction group. However, the LEAP (Lower Extremity Assessment Project) study demonstrated that functional outcomes were similar between amputation and limb reconstruction groups. Most functional measures used in this type of research are global in nature. Given that a substantial proportion of the patients in our study had bilateral injuries, the use of global scores makes it difficult to compare limb amputation with limb salvage. There is controversy about the utility of functional outcome measures to assess rehabilitation even for patients who have had a unilateral amputation. Groom and Coull noted that only five of twenty military personnel who had sustained a lower-limb amputation in the Falklands War had returned to some form of military service at two years postinjury. Dougherty found that soldiers who had sustained a unilateral transtibial amputation but no other injury in the Vietnam War had Short Form-36 (SF-36) scores that were similar to those of age-matched controls after twenty-eight years of follow-up. However, those with additional injuries performed significantly worse. Given that the majority of the casualties in our series had substantial concomitant injuries, it is possible that their long-term outcomes will also be compromised.
research; therefore, mitigation experts have been forced to develop injury criteria on the basis of automotive crash data. Our study demonstrates that, although there are some similarities between civilian and military complex foot injuries, the severity of the soft-tissue injury and the segmental nature of blast foot injuries make them far more severe. The data derived from this study are currently being used to evaluate and develop new models of injury. It is anticipated that, with the development of accurate injury prediction models, it will be possible to improve protection of the lower limb from explosion. This will probably require a multimodal approach, involving improvements in vehicle design (such as alterations of vehicle hull geometry [a “v-shaped” hull]), reducing the impulse transferred from the vehicle to the lower limb (e.g., with use of false-floor designs and energy-attenuation mats), as well as optimization of footwear to improve energy absorption or to transfer energy away from the vulnerable hind-foot segment to a limb segment that is more amenable to surgical reconstruction.18,28,30

Appendix

Tables showing the FASS categories and the injured foot and ankle segments as well as figures providing a diagrammatic representation of an anti-vehicle mine explosion, the proportion of foot and ankle segments injured in the blasts, a three-dimensional computed tomography reconstruction of a segmental fracture pattern, the distribution of the FASS scores, and the occupational outcomes are available with the online version of this article as a data supplement at jbjs.org.

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References


