Ballistic Trauma: Lessons Learned from Iraq and Afghanistan

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Abstract

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Management of upper extremity injuries secondary to ballistic and blast trauma can lead to challenging problems for the reconstructive surgeon. Given the recent conflicts in Iraq and Afghanistan, advancements in combat-casualty care, combined with a high-volume experience in the treatment of ballistic injuries, has led to continued advancements in the treatment of the severely injured upper extremity. There are several lessons learned that are translatable to civilian trauma centers and future conflicts. In this article, the authors provide an overview of the physics of ballistic injuries and principles in the management of such injuries through experience gained from military involvement in Iraq and Afghanistan.

During military conflicts, advances in trauma critical care and surgical management have resulted in important lessons learned from concepts applicable to the civilian health care sector.^{1–3} During the recent Iraq and Afghanistan wars, advances in modern body armor, logistical deployments, continued sustainment of forward surgical support operations, damage control resuscitation and surgical techniques, and rapid evacuation global transport systems have provided for increased survivability from battlefield ballistic trauma. For ballistic extremity injuries, fastidious use and widespread application of tourniquets have directly contributed to the reduction of exsanguinating hemorrhagic deaths, while also contributing to increased extremity reconstruction and salvage cases.^{4,5}

Many of the aforementioned military contributions to combat casualty care have also been credited to impacting recent civilian mass casualty events and other related medical care

areas. For example, the Boston Marathon bombing mass casualty incident in 2013 highlighted the effective transfer of lessons learned from combat casualty care to aid in the provision of effective medical, reconstruction, and rehabilitation care in areas such as triage, extremity and limb salvage, as well as amputee care.^{6,7} Adoption of massive transfusion protocols outlined within our military clinical practice guidelines have also contributed to improved outcomes in various applications within civilian trauma. These transfusion protocols have identified the important need for individual component therapy replacement to be a 1:1:1 ratio of red blood cells (RBCs):plasma:platelets and considerations for whole-blood transfusion parameters for certain massive hemorrhagic injuries.^{8,9} Finally, several refinements and next-generation devices have been realized within the field of prosthesis design including interfacing strategies with the residual limb, biologic and neurologic/muscle control systems, and haptic sensors.^{10–14}

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The ballistic and/or blast mechanisms of battlefield trauma, certain civilian accidents or criminal events, and terrorist acts can result in some of the most challenging, severe mangled extremity injuries that surgeons must address. Previous reports have estimated that upwards of 250,000 upper extremity ballistic injuries occur annually within the United States with upward peaks during periods of major conflict.^{15,16} In fact, ballistic injuries from firearms and gunshots were the third-leading cause of injury-related deaths nationwide in the United States during 2010.¹⁷ Furthermore, during the Iraq and Afghanistan conflicts from 2003 to 2014 there have been over 6,700 total deaths versus over 11,000 deaths by firearm in the United States during 2011 alone.¹⁸ Thus, ballistic injury events remain a major source of mortality and morbidity both within the United States as well as overseas.

Understanding Ballistic Physics

Traditionally, ballistics have been defined in terms of their specific projectile velocities (in feet or meters per second; fps or m/s), with low-velocity projectiles being less than 2,000 fps or 600 m/s and high-velocity projectiles being greater than 2,000 fps or 600 m/s.¹⁹ Low-velocity projectiles are often representative of handguns and/or shotguns, while high-velocity projectiles consist of rifles, military-grade weaponry, and improvised explosive devices or explosive events. However, division of ballistics by their velocities alone does not truly translate to their contributions to tissue injury and damage. For example, shotgun wounds at close range are often associated with significant tissue destruction despite being considered a low-velocity projectile source.

Rather than defining ballistics as low- or high-velocity, it is better to consider such mechanisms of extremity trauma as being low-energy versus high-energy.¹⁶ Both low-energy and high-energy projectiles lead to tissue damage based on the direct transfer of kinetic energy ($KE = \frac{1}{2} MV^2$) to the extremity and tissue that is impacted. Therefore, though the mass of the ballistic material is a contributor to tissue damage, the velocity of the projectile is the most important given its exponential role in increasing energy transfer, and it is this energy transfer that translates to direct tissue injury patterns evidenced by ballistic trauma.¹⁶

Overall, the projectile energy transfer is based on several factors. These factors include (1) projectile caliber, design, and composite materials; (2) projectile velocity; (3) kinetic energy of the projectile at bodily impact; (4) distance traveled prior to striking the body and after bodily penetration; (5) entrance profile and path of travel through the body; and (6) biologic characteristics of penetrated tissue.^{19–21} Given the above characteristics, handguns, CO₂ cartridge pellets, and BB guns can be thought of as low-energy ballistics, whereas shotguns, rifles, military-grade weapons, and explosive devices—formal or improvised—are representative of high-energy ballistics with varying levels of soft tissue and bone involvement.

As the ballistic penetrates the extremity and its associated soft tissues, the projectile causes both a permanent and a

temporary cavitation event.²⁰ For low-energy projectiles, the permanent cavitation event is directly associated with the actual tissue destruction as temporary cavitation is rather limited. These low-energy projectiles tend to cause localized tissue damage that is directly proportional to the actual size of the projectile itself. Conversely, high-energy projectiles have multiple mechanisms of tissue destruction secondary to the tremendous forces dissipated on the surrounding tissues due to the temporary cavitation effect. This effect initiates stretching, tearing, and crushing injuries to soft tissue in addition to thermal energy dissipated by the projectile and during energy transfer.^{15,16,19,21} The corresponding cavitation effect and temporary tissue expansions cause increased collateral damage due to shear, percussion, and vibratory forces that extend well beyond the permanent cavitation event.^{19–21} Thus, high-energy ballistic extremity injuries, especially combat-related and/or blast exposures, often result in composite tissue defects composed of unstable fractures, severe soft tissue avulsion and/or losses, varying degrees of thermal injury, as well as potential contamination with embedded particulates and foreign materials.

Combat and domestic improvised explosive devices (IEDs) deserve special consideration and mention as they result in additional trauma to the soft and hard tissues that extend far beyond that of typical ballistic patterns of permanent and temporary cavitation effects seen with handguns, shotguns, or even high-powered rifles. In addition to direct tissue damage from blast exposure, blast casualties experience a variety of differing mechanisms of injury to their bodies. Such injuries encompass both low- and high-velocity ballistic penetrating patterns while also inflicting components of burn, blunt, crush, and shockwave trauma concurrently. The shockwave mechanism is especially critical in wounding patterns, as it often causes extreme shearing, stretch, and avulsive forces that result in much more extensive injury than that noted by the initial visual inspection of the blast victim. These forces rapidly and forcibly travel through soft tissue planes along the paths of major peripheral and central nerves, veins and arteries, while also contributing shear injury to muscles and tendons (—Figs. 1A,B). Often, the blast pressure waves force foreign particulates throughout the extremity, and in conjunction with the corresponding pressure waves, direct injury occurs to the vascular structures as well as perineurial, perivascular, paratenon, and periosteal tissues. This situation can make decontamination of embedded foreign materials difficult and potentially compromise upper extremity salvage efforts. Finally, these mechanisms of injury may impact not only a substantial portion of the involved upper extremity, but often also adversely affect other body surfaces or tissues that provide workhorse reconstructive flaps or tissues used in extremity salvage and coverage.^{22,23}

Initial Considerations in Treating Low-Energy, Upper Extremity Ballistic Trauma

Within the urgent care or emergency room, the type of ballistic event (low or high energy), the extremity or extremities involved, dominate handedness of the patient, vocation,

Fig. 1 (A) Example of the extreme shearing, stretch, and avulsive forces to the right upper extremity secondary to explosive ballistic injury. (B) Same extremity after salvage via serial débridements, conversion of external fixation to internal rigid fixation, and coverage with latissimus dorsi muscle flap and skin grafting.

and potential concomitant injuries should be recorded and reviewed. Although a majority of low-energy ballistic trauma events are isolated in nature, a careful history and thorough physical exam is warranted to rule out potential life-threatening injuries or secondary injuries. A thorough upper extremity exam must be performed documenting physical findings of specific digits and/or level of upper extremity involvement, complete peripheral nerve and vascular integrity, muscle tendon function, and concomitant fractures and joint injuries.

Radiographs are important to aiding in the anticipated operative course as the ballistic course or tract can be identified and plans for the management of associated orthopedic fractures can be determined. For diaphyseal and metaphyseal fractures from ballistic trauma, structural defects can often be expected.²⁰ In cases of articular and/or joint involvement, these types of structure injuries increase the complexity and significantly affect functional outcomes as rehabilitation delays and potential motion loss are often encountered.²⁰ Significant orthopedic injury also heightens one's suspicion of potential nerve and/or vascular injury. Injuries to these structures can increase patient morbidities as loss of sensation and/or prehension, increased issues of pain, hyperesthesia, and/or dysesthesia. Thus, nerve blocks and optimizing pain management is crucial to patient comfort, recoverability, and rehabilitation. Additionally, for low- and high-energy ballistic injuries where repeat procedures are anticipated in an effort to gain control of the wound, the application of extremity nerve blocks is an important consideration and of benefit.

As long as there are no signs or findings of orthopedic fractures, complete tendon disruption, or vascular compromise, most low-energy projectile injuries can undergo irrigation and débridement procedures with consideration of

simple tractotomy and a short antibiotic treatment course. Plain radiographs should be obtained to assess retained ballistic fragments, course of projectile assessment, and to evaluate for potential orthopedic involvement. In cases of suspected nerve injury, most often neurapraxia rather than complete nerve transection is the cause. Thus, those ballistic injuries having findings of nerve involvement should be reassessed for recovery with exploration of the nerve performed if no signs of improvement are noted or findings on electromyogram are suggestive of a partial or complete nerve transection. When the low-energy ballistic injury involves an orthopedic fracture or direct penetration of a joint, then care must be given to a thorough débridement and washout of the involved fracture and/or joint with appropriate stabilization measures and a more prolonged course of antibiotics is typically warranted.

In the case of orthopedic involvement, increased suspicion for concomitant nerve and vascular injuries should be heightened and carefully assessed prior to operative intervention. Early evidence of progressive limb ischemia is a poor prognostic sign, and emergent repair of a vascular injury is warranted to provide limb salvage. Shortened and/or deformed fractures should be reduced with hemorrhage temporarily controlled either by direct pressure or tourniquets. Alternatively, in stable patients without signs of progressive ischemia or active bleeding, prehospital tourniquets should be carefully loosened and Doppler ultrasound assessments of ulnar and radial pulses should be performed along with ankle-brachial indices (ABIs) between the involved extremity and the noninvolved extremities.²⁴

Initial Considerations in Treating High-Energy, Upper Extremity Trauma

The vast majority of ballistic injuries experienced in war are more commonly the result of high-velocity missiles and/or high-energy injury mechanisms. The improvised explosive device (IED) is the preferred weapon for insurgents in Iraq and Afghanistan, and represents the highest energy-wounding mechanism, often combining multiple missile wounds with severe blunt trauma and burning from the explosive. The initial treatment of the upper extremity begins in the setting of the inciting event. As recent battlefield and Boston experiences have illustrated, prehospital tourniquets have greatly contributed to a reduction of hemorrhagic deaths within the War Theater and civilian sector while increasing the potential for salvageable upper extremity injuries with vascular injuries. The combat application tourniquet (CT, 2005; Composite Resources, Rock Hill, SC) and hemostatic agents such as Quickclot (Quickclot, 2005; Z-Medica Corp., Wallingford, CT) are carried by combat and medic personnel on the frontlines to provide for buddy aid and site of initial injury care. For those extremity injuries without vascular injury, direct compression of the extremity wound with a dressing can be useful during transport to the receiving treatment center.

Ballistic wounds are commonly treated within a multidisciplinary damage control resuscitation algorithm.²⁵ As

treatment priorities allow, the type of ballistic event (low- or high-energy), the extremity or extremities involved, dominant handedness of the patient, and concomitant injuries should be recorded and reviewed. Once life-saving matters are assessed and appropriately triaged, limb-saving and extremity injuries are addressed. A thorough upper extremity exam must be performed documenting physical findings of specific digits and/or level of upper extremity involvement, complete peripheral nerve and vascular exams, flexor and extensor tendon functions, potential bony deformities or instabilities, and whether there is direct injury to a joint or joint surface.

As mentioned within the low-energy section, radiographs are critical in high-energy ballistic injuries in the information on the ballistic course of tissue destruction and potential severe collateral injuries. Combined structural orthopedic injury patterns are usually evident, with comminuted diaphyseal and/or metaphyseal fractures often present in addition to varying levels and complexities of articular and/or joint involvement. Actual loss of tissue due to the avulsive nature of high-energy ballistics leads to varying amounts of devitalized soft tissue; and bone, segmental bone, and/or articular surface loss and destruction; it also increases the rate of concomitant muscle, tendon, nerve, and/or vascular involvement (►Fig. 1). These combined injury patterns contribute to high morbidity with prolonged treatment courses expected including difficulties in rehabilitation, loss of sensation and prehension, increases in hyperesthesia and/or dysesthesia, extended periods of soft tissue rest, as well as potential delays in definitive soft tissue coverage with consideration for and the timing of staged reconstruction procedures. In these cases, nerve blocks and aggressive pain management regimens are requisite as the need of prolonged pain control measures is fairly certain.

Importantly, the timing of specific management aspects of these injuries must be taken into consideration. The patient must be resuscitated, the wounds must be managed appropriately, and reconstruction must be planned. Depending on the severity of the injury, concomitant injuries, and complexity of the reconstructive goals and possibilities, the course of treatment can be very long and protracted. As these patients suffer polytrauma, undergoing long, reconstructive procedures is inappropriate in the setting of underresuscitation. In addition, the wounds often have large zones of injury that continue to manifest over time necessitating multiple débridement procedures. The principles of damage control must be applied, especially in the setting of the battlefield.

The first step is early and aggressive débridement. The idea of débridement was first formally defined at the Inter-allied Surgical Conference in 1917, at which it was determined that an adequate débridement consisted of excision of nonviable skin, generous extension of the wound through all layers, and excision of damaged muscle and contaminants.²⁶ Following débridement, all wounds are copiously irrigated with normal saline.²⁷ Devitalized tissue and gross contamination, in addition to being detrimental to reconstruction, are potential niduses for infection. The high-energy nature of these injuries often necessitates multiple serial débridement procedures,

typically performed every 2 to 3 days, as the zone of injury is extremely wide and the amount of débridement necessary may not be readily apparent at initial presentation. In addition, fractures must be stabilized in an expeditious manner using methods that minimize physiological harm to the patient. Kirschner wires, external fixators, and plaster splints remain the mainstay of fracture care in the setting of damage control surgery.

Prevention of infection is paramount. Early administration of antibiotics is key to decreasing infection rates in open fractures and amputations. It is important in these injuries to administer antibiotics with appropriate coverage for the environment in which the injury occurred. In addition, as an adjunct to débridement, in high-grade open fractures and wounds, polymethylmethacrylate antibiotic bead pouches can be used to deliver a high concentration of antibiotics locally when necessary.

Early wound coverage may not be feasible in the setting of certain high-energy ballistic injuries due to the progressively increasing amounts of nonviable tissue and deeply impacted debris. Various wound care strategies including negative pressure wound therapy are important adjunctive tools in managing such wounds prior to definitive reconstruction and coverage. Use of negative pressure wound therapy is now standard practice among military surgeons due to the improved wound granulation, wound contraction, control of wound exudate, decreased edema, and improved pain management, and often remains the dressing of choice until definitive wound coverage can be achieved.^{28,29} Additionally, in heavily contaminated wounds or wounds with increased risk of fungal infection, distillation of antibiotic and/or antifungal solutions in combination with negative pressure therapy has shown to be quite beneficial throughout the care of severe high-energy ballistic traumatic injuries until definitive coverage can be safely achieved.

The Use of Spare Parts

The concept of spare parts surgery has been used to treat the mangled upper extremity since before 1950.³⁰ Adjacent tissue from unsalvageable digits can be used to cover palmar defects. In the polyextremity blast trauma, when adjacent tissue may not be available, free tissue transfer of spare part(s) is often used to restore function. Great-toe-to-thumb transplantation can restore grip and grasp.³¹⁻³³ In the case of the war-injured patient with traumatic amputations or near amputations, the great toe can be harvested and banked for definitive transfer at a tertiary care facility (►Figs. 2A-C).³³ Careful consideration of banking any potential available spare parts has also been a critical addition to our reconstructive armamentarium. Tissues such as cartilage, tendon, and bone have all been successfully banked and used in secondary or tertiary autologous tissue based reconstructions for several of our high-energy ballistic injured patients with acceptable results.

Major Vessel Injuries

Ballistic injuries often cause complex extremity injuries with skeletal, vascular, and nerve injuries with large soft tissue

Fig. 2 (A) Left-hand wound with traumatic thumb and small finger amputations, palmar soft tissue defect secondary to high-energy ballistic injury. (B) Left-hand injury after débridement, ring-finger fillet of finger flap for palmar coverage, and heterotopically banked left great toe to forearm position performed in the battlefield theater. (C) Left-hand reconstruction after banked great-toe-to-thumb transfer and dermal regenerate matrices incorporation followed by skin grafting at 1-year follow-up.

defects.^{34,35} Isolated arterial injuries occur less than 10% of the time.³⁵ Patients with ballistic upper extremity injuries should undergo surgical exploration at the time of initial treatment to rule out vascular injury. Angiography may not only assist in diagnosis of vascular injury, but also determine the nature and location of injury for surgical planning.

As previously stated, major vascular injury in the upper extremity is initially treated with a tourniquet. After arrival at a facility with surgical capabilities, upper extremity ballistic injuries with major vascular injury may benefit from temporary shunt use for severe vascular injuries. The Balad Vascular

Registry reported 86% patency rates with temporary shunt use, which has directly contributed to increased vascular repair and limb salvage success rates by allowing for transportation to higher-level-care facilities for definitive repair techniques.^{24,36,37} In cases with concomitant skeletal injury and bony misalignment, temporary shunting is used until skeletal fixation can be achieved.³⁸ Once bony stabilization has been achieved and the patient is physiologically stabilized for a definitive operation, the shunt should be replaced with a permanent graft. Vein grafts are preferred and saphenous grafts are harvested when available. However, in the poly-extremity-injured patient, adequate vein sources such as the saphenous vein, may not be available thus requiring the use of conduit and synthetic grafts. Vascular patency should be checked prior to final skeletal fixation to ensure inadvertent compromise of the repair.³⁹

The majority of venous injuries are treated with ligation or primary repair where possible. Vascular injury also increases the rate of subsequent upper extremity deep venous thrombosis, which may result in further vascular compromise. However, further definitive reconstruction can be performed safely in the setting of proximal deep venous thrombosis in combination with therapeutic anticoagulation.⁴⁰ The risk of upper extremity compartment syndrome after revascularization remains high; therefore, fasciotomy after prolonged ischemia time is recommended.³⁵ Exposed vessels or repairs of any type should be protected from direct contact with negative pressure wound dressings and should be covered with well-vascularized tissue after appropriate débridement of the surrounding wound. Our group has found no increased tissue transfer or failed upper extremity limb salvage in patients who have undergone a successful proximal revascularization procedure after an injury secondary to ballistic trauma.³⁴ Further, definitive extremity reconstruction procedures will likely need to be performed in the setting of antiplatelet or anticoagulation to protect the repair. Vascular repairs should be monitored according to institutional protocol.

Nerve Injury

Concomitant nerve injuries are concerning and may have significant impact on functional status of the affected extremity.^{35,41,42} Ballistic wounds increase the risk of nerve severance and irreparable damage.⁴³ Nerves can be repaired primarily or with autologous nerve grafts in situations where the nerves are deemed viable. However, it is important to note that ballistic injuries may result in significant proximal and distal nerve injury beyond what is immediately apparent. Moreover, varying levels of complexity for mixed nerve injury patterns (MacKinnon classifications 1–6) and segmental defects are often apparent on exploration of nerve injuries. Definitive treatment should be delayed until the extent of injury is determined.

Simple and complex nerve repairs can be safely performed in conjunction with soft tissue transfers and complex orthopedic procedures in an effort to salvage severely injured upper extremities. However, nerve repair or reconstruction

Fig. 3 (A) Left upper extremity gunshot wound with large exit site and segmental ulnar nerve defect. (B) Same injury after débridement, segmental ulnar nerve defect reconstruction with interposition nerve allograft of 6 cm and nerve coaptation wraps in place. (C) Primary closure of left upper extremity gunshot wound after repair of segmental ulnar nerve defect with allograft.

should not be attempted until complete evolution of the zone of injury is realized to ensure healthy nerve endings following débridement to maximize nerve regeneration. Sural nerve harvest can be performed open or endoscopically, with nerve allografts having also shown promise in addressing segmental nerve defects (►Figs. 3A-C).⁴⁴ After repair, patients should be followed with clinical and electrophysiological examinations. Physical and occupational therapy is key to minimize functional deficits. Pain following reconstruction of the upper extremity after ballistic injury is a common complaint and neuroma formation is a possible complication after nerve repair in this setting. Due to the poor prognoses for functional recovery following repair or reconstruction of large peripheral nerve gaps resulting from combat-related

injuries—especially in injuries above the elbow—consideration should be given to alternative reconstruction techniques such as nerve transfers, tendon transfers, and target muscle re-innervation.⁴⁵

Specific Considerations by Level

Hand and Wrist

Digital injuries have a significant propensity to develop stiffness secondary to inflammation. Single digital amputations through zone 2 are not replanted in the civilian trauma setting secondary to poor outcomes and its potential expendability in isolation. In a combat setting following such trauma, microsurgical capability is often not available, so revascularization of digits is often unable to occur. In general, all initially salvageable digits should be maintained when possible. Subsequently, the dysfunctional digits can be reconstructed, reconsidered for spare parts, or serve a new function, such as pollicization. The thumb should be salvaged if possible and be given a priority for reconstruction—given its significant role in hand function (> 40%). Such an approach allows the patient an opportunity to undergo therapy and secondary procedures as necessary to improve function. If possible, prehensile function can be maximized by digital nerve grafting or direct repair. Tendons and pulleys may be reconstructed. Various forms of arthrodeses or arthroplasties may be used to optimize function in the setting of absent or dysfunctional tendons. However, it is not unexpected for patients to experience high rates of stiffness and decreased range of motion of the individual digits that may or may not be amenable to surgical improvement.

Blast injury to the hand results in a typical pattern of palmar hyperextension, thumb and finger hyperabduction, interphalangeal joint and metacarpophalangeal joint hyperextension, and dorsal dislocation. Patients frequently sustain significant palmar tissue destruction.³¹ The impact can be tremendous as the palm (distal to the wrist crease) houses the important structures key to perfusing the digits. Repairs of the superficial, deep, and dorsal arches and the radial and ulnar arteries at this level are crucial to maintaining hand vascularity. In addition, it is important to note that it is highly likely that the interosseous, thenar, and hypothenar muscle bellies are also involved. The palm itself may experience segmental losses of bone and soft tissue requiring complex reconstruction in the setting of intact digits. Loss of multiple metacarpals may require osteocutaneous free tissue transfers or bulk corticocancellous or cortical autograft. Soft tissue coverage, especially at the dorsum of the hand, usually requires a free or pedicled tissue transfer rather than tissue repair (►Figs. 4A-E).

When ballistic injuries involve the wrist, care must be taken to achieve a carpal reduction and temporary stabilization, typically achieved with Kirschner wires, wrist spanning external fixation, and/or bridge plates as indicated. Posttraumatic osteoarthritis is common, but does not typically follow traditional patterns of degeneration as seen in lower-energy interosseous ligament injuries, and may require salvage with partial or total arthrodesis as indicated. Ballistic injuries that

Fig. 4 (A) Radiography illustrated left-wrist ballistic injury with severe destruction and loss of multiple carpal bones and external fixation in place for maintaining length. (B) Radiograph of same injury after conversion of external fixation to internal fixation and soft tissue coverage. (C) Left-wrist ballistic injury prior to definitive reconstruction. (D) Left-wrist ballistic injury following repair of multiple tendon injuries. (E) Left-wrist ballistic injury after free lateral arm flap for coverage of extensor tendon repairs and hardware.

involve the distal radioulnar joint can be challenging, leading to significant pain and loss of function. Distal ulna fractures have been commonly encountered in the past decade associated with ballistic and blast injury mechanisms. Distal ulnar resection or implant arthroplasty may be used in highly comminuted fractures failing fixation, or for pain and functionally limiting posttraumatic osteoarthritis.

Forearm Level

At the forearm, single radial or ulnar artery injuries can be ligated if collateral flow is confirmed. However, in high-energy ballistic injuries, both vessels are likely to be in the zone of injury and damaged to some degree. If repair is possible without risk of significant morbidity to the patient, repair is recommended over ligation. If both vessels are injured, traditionally ulnar repair or reconstruction is preferred as it is most frequently the dominant vessel to the superficial arch.^{39,46–48} It is important to note that there is considerable variation in contributions of both radial and

ulnar arteries to hand perfusion. The superficial arch is complete 78% of the time, and the deep arch is complete 97% of the time.⁴⁸ Furthermore, one study of dominance as measured by pulse volume plethysmography amplitudes in 100 normal volunteers demonstrated higher frequency of radial dominance, which was especially pronounced in the thumb and index finger.⁴⁹ Accordingly, the recent literature argues that preserving both ulnar and radial arteries may be important for long-term perfusion of the hand, reviewed by Chim et al.⁵⁰ In the acute setting, when considering ligation, perfusion to the digits should be investigated noninvasively (i.e., Doppler examination). Also, as it may not be practical to repair or reconstruct both arteries, consideration should be given to future reconstruction. In addition, this should be kept in mind when considering harvesting a radial artery forearm flap.

High-energy trauma often imparts significant soft tissue destruction that can put the forearm at high risk for compartment syndrome. A high index of suspicion and a low

Fig. 5 (A) Computed tomography image demonstrating severe destructive nature of right humerus secondary to military-grade ballistic—an AK47 round. (B) Radiograph of right humerus reconstructed with vascularized free fibula transfer 2-years postreconstruction. (C) Right upper extremity salvage 2-years after free fibula for humeral reconstruction. Patient can perform 27 pullups with extremity reconstruction and maintained active duty status during this 2-year period.

threshold for compartment releases must be practiced. The most often involved compartment is the volar compartment, most often damaging the deep finger flexors. Volkmann's ischemic contracture is a devastating complication of unrecognized forearm compartment syndrome and may require free functioning muscle transfer to restore function in replacing damaged muscle bellies.

Initial stabilization of long bone fractures of the forearm may be accomplished with external fixation, with addition of Kirschner wire fixation as needed, whereas eventual fixation may be accomplished with plate and screw fixation. Various techniques have been described for the treatment of smaller bone defects, including the use of autograft and allograft bone, and bone substitutes, whereas vascularized bone grafts and use of composite tissue grafts may be required for larger defects and more complex injury patterns (►Figs. 5A-C).⁵¹

Elbow Level

Ballistic injuries at the elbow level often present themselves as a very complex reconstructive problem in both bony and soft tissue categories. This is an area with limited soft tissue redundancy that is unforgiving in terms of soft tissue coverage as well as damage to peripheral nerves.

The elbow joint consists of ulnohumeral, radiohumeral, and radioulnar articulations, none of which are tolerant of much articular incongruity. Periarticular elbow fractures are treated by standard open reduction and internal fixation procedures with plate and screw constructs. Comminuted radial head fractures can be managed with arthroplasty or resection as indicated. In addition, it is important to note the importance of the ligaments and bony congruity that impart stability to the elbow. Biomechanically large coronoid fractures must be addressed. The lateral ulnar collateral and medial collateral ligaments should be kept intact, repaired, or reconstructed. The elbow joint is unforgiving and is prone to stiffness and formation of heterotopic ossification. After maximization of physical therapy, contracture release and

heterotopic ossification resection may be necessary to maximize range of motion, which will provide results comparable to lower energy civilian trauma.⁵² There are few effective salvage procedures for decimated joint surfaces as total elbow arthroplasty is not durable enough to be practical in a young, active population, and elbow arthrodesis may provide a more durable long-term solution.

Arm and Shoulder Injuries

War-related injuries to the brachium and shoulder frequently involve gunshot wounds and blast injuries, and are often associated with significant torso injury with intrathoracic and intra-abdominal components. Brachial-level injuries may be too proximal for tourniquet application. Vascular control at the level of the axillary or subclavian artery may be required to prevent unchecked blood loss and exsanguination, and temporizing use of vascular shunts may be required until definitive vascular repair or reconstruction can be achieved. Peripheral nerve injuries with large segmental nerve gaps have poor prognosis. Repair or reconstruction is typically indicated, but consideration for functional augmentation with tendon transfers is usually advisable.

In war-related blast injuries, the soft tissue of the torso may be protected by body armor. As a result, pedicled latissimus dorsi or scapular flaps may be considered to cover proximal defect. The humerus can be shortened up to 5 cm to reduce soft tissue defects to allow for primary closure as well as other alternatives such as wound closure devices or dermal substitutes to allow for later skin grafting of defects.

Humeral shaft fractures can be treated successfully in a closed fashion utilizing various popular techniques, including functional bracing. Initial stabilization of open fractures is usually performed by external fixation until definitive fixation is indicated, which typically will consist of plate and screw fixation or intramedullary device based on surgeon preference and fracture characteristics (►Fig. 5).

Limb Salvage versus Amputation

The decision to attempt limb salvage or to perform an amputation in the upper extremity can be a difficult decision, especially in the frontline combat setting. In the upper extremity, the generally accepted absolute indication for amputation is a warm ischemia time greater than 6 hours, although this may extend to 8 to 10 hours. Additional indications may include the crushed extremity with arterial injury. The surgeon should carefully consider and question the need for emergency flap coverage after war-related ballistic trauma, as it has been fraught with failure, and usually reflects severe destruction to local tissues and a large zone of injury. In such instances, amputation may be more advisable. Unlike in the lower extremity, functional prosthetic function has not approached the native function of the human arm and hand. Generally, if there is the expectation for preservation of hand prehension and sensation, and barring the absolute indications for amputation, limb salvage should be attempted. Upper extremity amputations after military injury are uncommon and have worse outcomes than lower extremity amputations, further emphasizing the superiority of the native hand to current prosthetic technology.^{53–55}

Further Lessons Learned: Advancements in Soft Tissue Coverage for Limb Salvage in Extensive High-Energy Ballistic Extremity Injuries

Given the changes in severity and challenges of the multi-extremity-injured combat casualty care patient, high volumes of massive soft tissue and composite type injury patterns have been increasingly encountered. These increasingly challenging wounds have led to our military reconstruction teams to utilize what we have termed the “hybrid reconstructive ladder/elevator.” This paradigm shift has contributed to great advancements and improvements in primary and secondary extremity reconstruction by incorporating various regenerative medicine therapies with traditional reconstruction techniques.

Regenerative medicine therapies, namely extracellular matrices for dermal regenerate templates or scaffolds, urinary bladder matrices, and other techniques have been instrumental in improving the durability of our reconstructions and decreasing ulceration or erosion of active and heavily used extremities in our amputee and limb salvage populations. Spray skin technologies have been used with early promising results and will likely be able to be extended to the civilian sector eventually. Autologous adipose tissue grafting for addressing secondary soft tissue defects, scarring, and/or tethering of extracellular matrices (ECMs), dermal regenerate templates (DRTs), and skin grafts to underlying tendons, muscles, or osseous structures have also had an increasing role in our ballistic injury cohorts. ECMs and DRTs are regenerative medicine approaches and are reconstructive materials that act as three-dimensional bioactive scaffolds, consisting of structural and functional proteins as well as may contain growth factors in certain instances. Bone-regeneration strategies for segmental osseous defects including bone transport, vascularized and/or non-vascularized bone grafting strategies, and mesenchymal stem cells in isolation or in conjunction with

scaffolds and/or composite chimeric flaps with bone and soft tissue components have been increasingly applied in reconstructions for limb salvage. Peripheral nerve regeneration strategies with allograft and/or autologous nerve components have been utilized in early settings of reconstruction.

Prosthetic and residual limb interfaces as well as neuroma treatment strategies with novel techniques such as target muscle reinnervation and implantable nerve/muscle signaling and control systems for better residual limb or salvaged extremities have continued to develop. Finally, vascularized allotransplantation has also shown to be beneficial in specific extremity injuries. All of the above areas have had increasing roles as complementary therapies and treatment strategies to our traditional reconstruction approaches with yet more to come.

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