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Review Article

Ballistic Nerve Injuries: State of the Evidence and Approach to the Patient Based on Experience

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A R T I C L E I N F O

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Nerve injuries secondary to gunshot wounds (GSWs) have been traditionally thought of as neurapraxic injuries with high likelihood of complete recovery. A review of the literature, however, highlights the misconceptions surrounding ballistic nerve injuries and their treatments. Contrary to this accepted dogma, approximately 30% to 60% of GSWs to the upper extremity may result in nerve injury requiring repair or reconstruction. Surgical exploration following ballistic injury reveals that 20% to 55% of nerves were lacerated requiring repair or grafting. Despite these numbers, outcomes after nerve repair or grafting are limited, and the limited data show evidence of poor functional recovery. In our experience, delayed exploration of GSW-related nerve injuries in patients without signs of functional recovery demonstrate large neuromas in continuity often requiring meticulous dissection and excision with resulting large gaps that require reconstruction. This has led us to explore options to identify patients with nerve deficits after GSWs who may benefit from earlier exploration. Others advocate for the exploration of all ballistic nerve injuries, which would represent a logistical challenge in high volume centers and may lead to unnecessary explorations of in continuity nerves. To facilitate identification of nerve injury following GSWs, we have explored the utilization of early ultrasound to identify patients with nerve lacerations that may benefit from early exploration (1–2 weeks after injury). Earlier exploration can lead to less technically challenging surgery, shorter nerve gaps, and more time for the nerve to recover. Herein, we present a series of cases to help illustrate this approach to the patient. Although early exploration and repair versus grafting of nerves may have benefits as outlined above, there are little to no data on outcomes of nerve repair or grafting in ballistic injuries in the more acute setting, 1 to 2 weeks after injury. Further research is needed both with regards to diagnosis and utilization of ultrasound, as well as postoperative outcomes in patients with ballistic nerve injuries to help guide our ever-evolving treatment protocols.

Ballistic trauma is a major public health issue in the United States with increasing rates over the Coronavirus Disease of 2019 pandemic.[1] As these ballistic injuries become more prevalent and less concentrated to urban centers, treating physicians must be familiar with the types of injuries that a gunshot can produce. With a ballistic injury, there is damage to the soft tissues secondary to (1) the direct path of the bullet and (2) temporary cavitation or the pressure wave created by the projectile, which is usually larger than the path of the bullet itself.[2] Both the direct path of the projectile itself and the area of temporary cavitation (stretch, shear, or concussive type injury) can produce significant damage to the surrounding soft tissues.

Traditionally, nerve injuries secondary to GSW were considered neurapraxic injuries with almost certain likelihood of recovery. The injury was thought to be a concussive type injury without laceration. When reviewing the literature, however, the incidence of no recovery or only partial recovery from these injuries is high, contrary to popular beliefs.[3]

Over a 3-year period, our department has seen 174 cases of documented GSW-related nerve injuries in the upper extremity alone. In treating these injuries, our experience is more reflective of the published literature than the traditional dogma that the vast

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majority of ballistic nerve injuries recover spontaneously. Thirty percent of these patients had confirmed nerve lacerations on exploration. Many of the remaining patients were lost to follow-up, however, making determination of rates of neurapraxia and clinical recovery difficult. Given the higher confirmed rates of nerve laceration and high rates of loss to follow-up, we have modified our approach to ballistic nerve injuries toward earlier identification and treatment of these injuries.

This article will review the current state of the literature on ballistic nerve injuries, examine how the literature and our experiences have informed our treatment with GSW nerve injuries using illustrative cases, and discuss both the current challenges and future directions in treating our patients with ballistic nerve injuries.

Ballistic Nerve Injury: What Is the Literature?

To better understand ballistic nerve injuries and their outcomes, one must begin with the work of George Omer. He published the largest and most complete evaluation of patients with nerve injuries secondary to GSW since World War II.[3,4] He followed 331 “low-velocity” and 264 “high-velocity” GSW nerve injuries treated nonoperatively in all patients at the Brooke Army Hand Center from 1966 to 1970 during the Vietnam war. His conclusion is as follows: “These results indicate that most gunshot wounds result in axonotmesis.”

Although 69% of both high- and low-velocity nerve injury patients had “spontaneous recovery,” this left nearly one-third of patients without any recovery from their nerve injury. Furthermore, of those 69% of patients with “spontaneous recovery,” it is unclear how many of these patients exhibited “good clinical recovery.”[3]

This is also one of the few studies that describes the outcome of nerve injuries managed surgically.[3] They performed a neurolysis (if the nerve was intact on exploration), nerve repair, or nerve grafting depending on findings at exploration. Most cases were performed between 3 and 6 months with few patients having good clinical recovery. Only 10/32 patients with low-velocity GSW injury nerve repair (6/18 above elbow and 4/14 below elbow), and 7/35 patients with high-velocity GSW injury nerve repair (4/21 above elbow and 3/14 below elbow) had a good clinical recovery (muscles regained function in consistent with nerve regeneration, independent movement against resistance, two point-discrimination of >20 mm). None of the 19 patients requiring nerve graft had return of clinical function. Furthermore, 40% of patients with the nerve in continuity (neurolysis performed) did not recover.[3]

Since that time, many authors have studied and reported on the incidence and recovery after ballistic nerve injuries. Veltre et al[5] analyzed 168 GSWs with associated radius and ulna fractures in a multicenter trial with 40% incidence of nerve injury. At the final follow-up, complete recovery occurred less than half the time (20% to 30% full recovery in the ulnar, median, anterior interosseous, and posterior interosseous nerve distributions).[5]

Straszewski et al[6] analyzed 117 patients with upper extremity GSW injuries, of which 38 (30%) had nerve injuries. Of the 38 patients at the final follow-up, 32% had no recovery and 44% had partial recovery. They explored 19 of these nerves during fracture fixation (1 in a delayed fashion) and found 15/19 nerves to be in continuity; however, we do not know the neurologic outcomes of these patients.[6]

Others have also published their experiences with surgical exploration ballistic nerve injuries. Pannell et al[7] published their case series on 37 nerves with a nerve palsy after ballistic injury of the upper extremity; 27% of these nerves were lacerated. The indications for surgery were not stated, but the authors advocated for early exploration of GSW injuries. Anantavorasakul et al[8] reviewed their series of GSW hand injuries noting that 47% of patients had nerve deficits. Of the 38% of patients who underwent operative exploration, 57% had a partial or complete transection of the nerve. Neither of these studies reported outcomes after surgery.

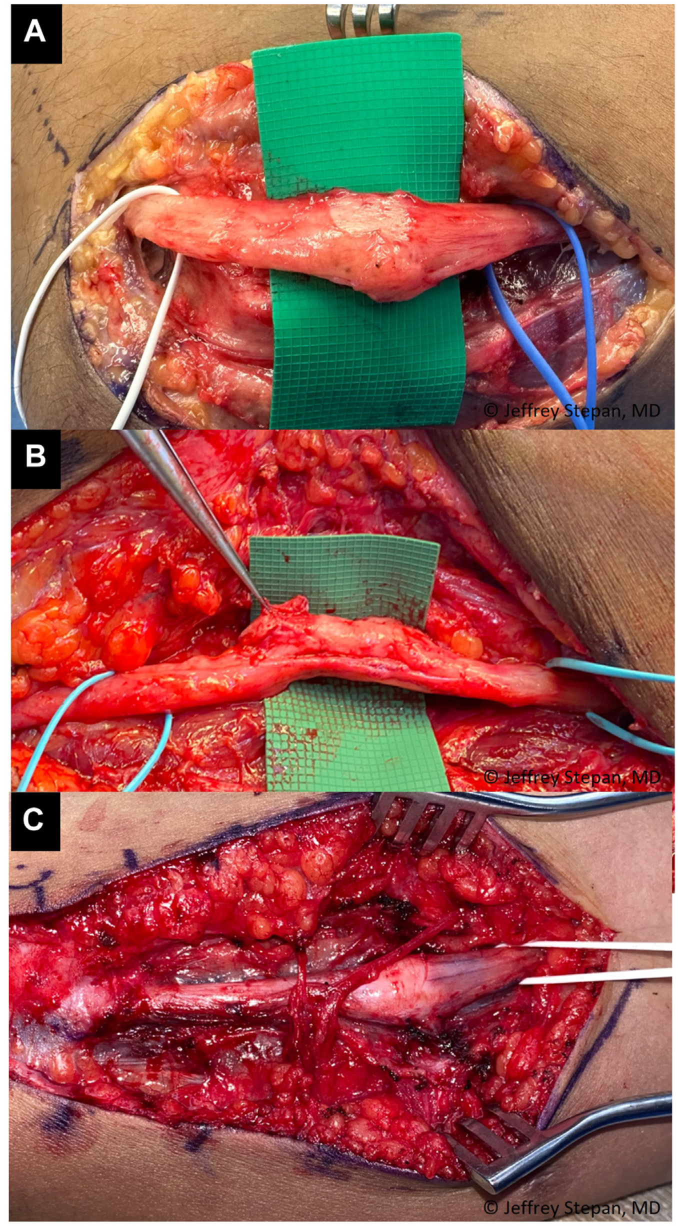

Figure 1. Examples of neuromas in continuity after GSW with no return of function. **A** Neuroma in continuity 2.5 months from GSW injury of the ulnar nerve at the elbow. **B** Neuroma in continuity 6 months from GSW injury of the ulnar nerve at the elbow. **C** Neuroma in continuity 3.5 months from GSW injury of the ulnar nerve proximal to the elbow.

Luce et al[9] published their experience with 77 shotgun injuries and presented limited outcomes data. Of the 77 shotgun injuries, 45 patients sustained a nerve injury, and they explored 31 of these nerves. Fourteen of 31 (45%) of the explored nerves were transected. The other 17 patients were noted to have contused or frayed nerves; only half of which had complete recovery.

These articles highlight the existing literature (of which there are many more similar studies), which demonstrates the incidence of nerve injury after GSW to the upper extremity is greater than 30% to 60% (increased incidence with higher energy ballistic

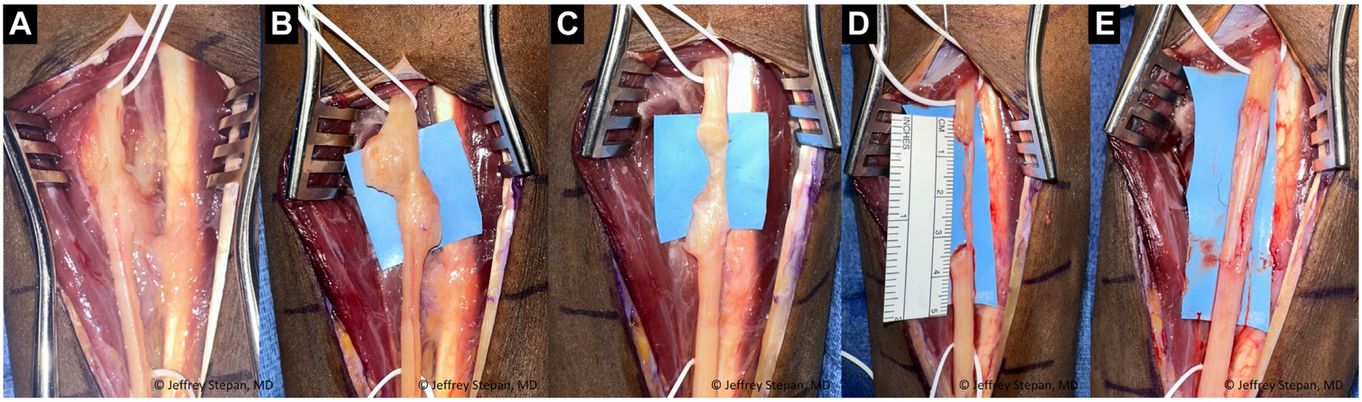

Figure 2. This patient sustained an injury to the ulnar nerve 2.5 months prior to exploration. The nerve was not explored during ulnar shaft fixation and referred to the hand service. **A** Large neuroma in continuity scarred to the surrounding soft tissues in the forearm. **B** Ulnar nerve dissected free from the soft tissues with large neuroma. **C** After excision of neuroma and internal neurolysis with a few remaining intact fascicles. **D** A 3-cm gap after cutting back to healthy fascicles. **E** Sural nerve cabled autograft to span the graft.

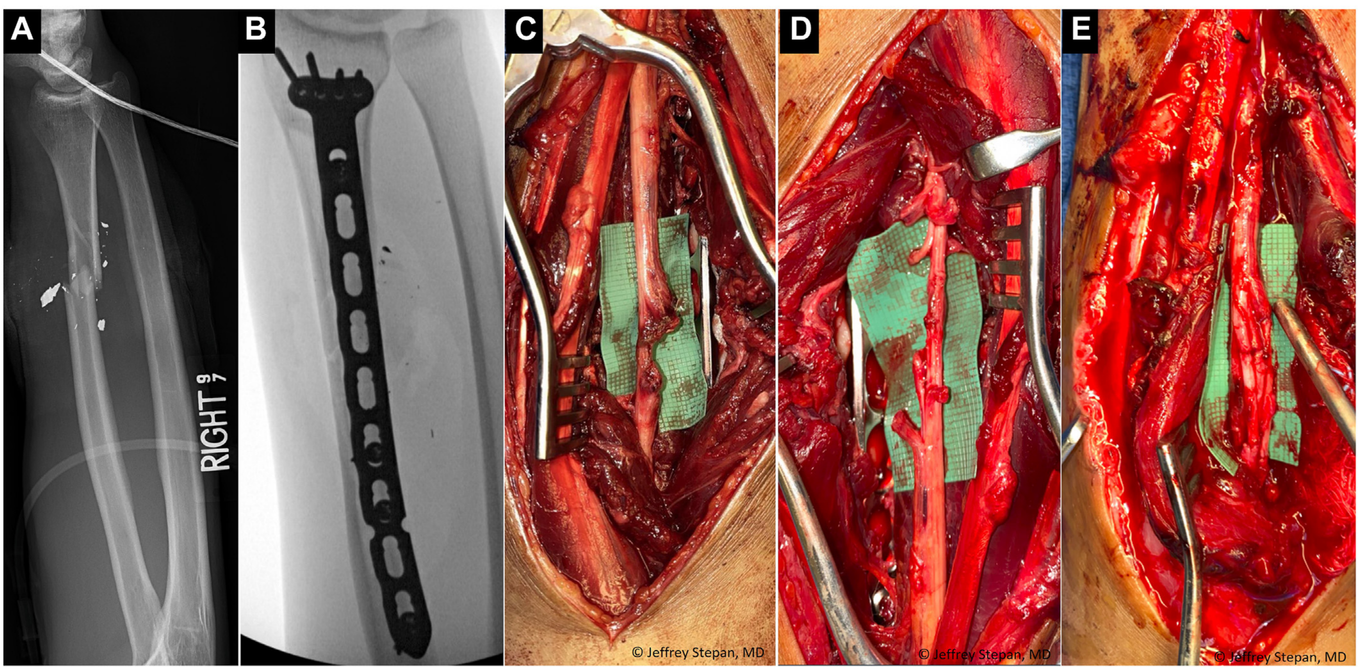

Figure 3. GSW injury sustained with median nerve deficit and radial shaft fracture. **A** Initial Spot film radiographs of the right forearm. **B** Intraoperative fluoro demonstrating fixation of the radial shaft fracture. **C** Exploration of the median nerve at time of fracture fixation 8 days after injury demonstrating a partial nerve laceration. **D** Intraneural dissection and identification of healthy fascicles and injured fascicles. **E** Nerve grafting of the median nerve.

trauma, vascular injury, and more distal GSW). In the studies that do present some outcome data of nonoperatively and operatively managed patients, it is clear that most patients do not have full return of clinic function.

The literature also highlights the challenges of both diagnosis of nerve injury requiring intervention and the timing of exploration. Upon early surgical exploration of patients with nerve deficits, less than half of patients had obvious complete or partial laceration. In patients with "intact" nerves on exploration, however, rates of incomplete recovery remain high at approximately 30% to 40%.[3,9] Despite some authors advocating for early exploration, outcomes after nerve repair and/or grafting in the literature are limited. There are even fewer data on the clinical outcomes in patients who had early surgical intervention and nerve repair or grafting. Omer's study was one of the very few to present any postoperative clinical recovery in these patients. Their patients had nerve repair or grafting usually performed between 3 and 6 months with good clinical recovery in less than 30% of their patients.[3]

Lessons Learned in Treating These Injuries

All gunshot nerve injuries are not neurapraxic injuries; mixed sunderland grade 6 injuries occur frequently

After a brief review of the literature above, it is abundantly clear that many nerve injuries from GSWs do not go on to full recovery. This has been our experience in treating high volumes of ballistic injuries. As more series of ballistic nerve injuries have been published in the last 10 years, this opinion has started to clearly shift as indicated by a number of other authors proposing early exploration of patients with nerve deficits after ballistic injuries.[7,10]

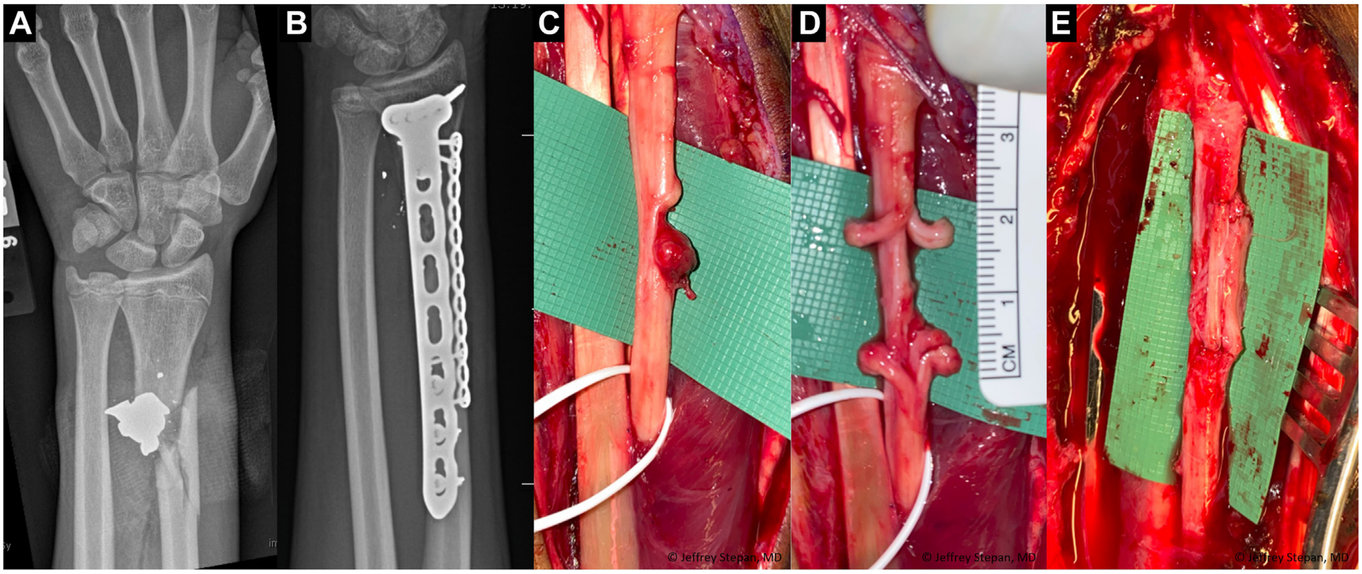

Figure 4. GSW injury sustained with partial median nerve deficit and radial shaft fracture. **A** PA wrist radiographs. **B** Intraoperative fluoro demonstrating fixation of the radial shaft fracture in a bridge construct. **C** Exploration of the median nerve at time of fracture fixation 10 days after injury demonstrating a partial nerve laceration. **D** Intraneural dissection and identification of healthy fascicles and injured fascicles. **E** Nerve grafting of the median nerve.

As noted above, many patients may have partial recovery from their nerve injury. This is likely secondary to the nature of ballistic trauma causing damage in both the direct path of the bullet and the concussive effect of the temporary cavitation. These two mechanisms of injury inflict varying degrees of damage onto a nerve. The cases of acute exploration to follow will be illustrative of how a nerve can undergo injury likely from the direct path of the bullet as well as suffer bruising and injury from the temporary cavitation. With this, patients with early partial recovery must be closely monitored until good clinical function returns as an intact nerve does not necessarily ensure a good clinical outcome.

Expect a neuroma in continuity on delayed exploration

Early in our experience, we treated these patients similarly to closed injuries with clinical examination and electrodiagnostic studies. We recommended operative exploration at 3 to 6 months after injury if there was no clinical return of function. Treatment would be delayed even further in patients with some initial return of function.

When we eventually explored these injuries, we most frequently encountered large neuromas in continuity (Fig. 1). Delayed exploration with a large neuroma in continuity leads to a difficult management problem especially in those patients with some but clinically insignificant return of function. These cases required tedious internal neurolysis through scar and often there are no viable appearing fascicles. When resecting these neuromas, to healthy appearing fascicles, a large gap remains requiring autograft of >3 to 4 cm (Fig. 2). Outcomes have been limited, even in our patients secondary to loss to follow-up.

Acute exploration allows easier dissection and shorter gaps

In patients with nerve injuries in the field of dissection for other concomitant injuries that require urgent attention (fracture, vascular injury, etc.), we recommend nerve exploration. If the nerve is in continuity at exploration, continued expectant management is important, given the number of patients that will not achieve good clinical function despite an intact nerve.

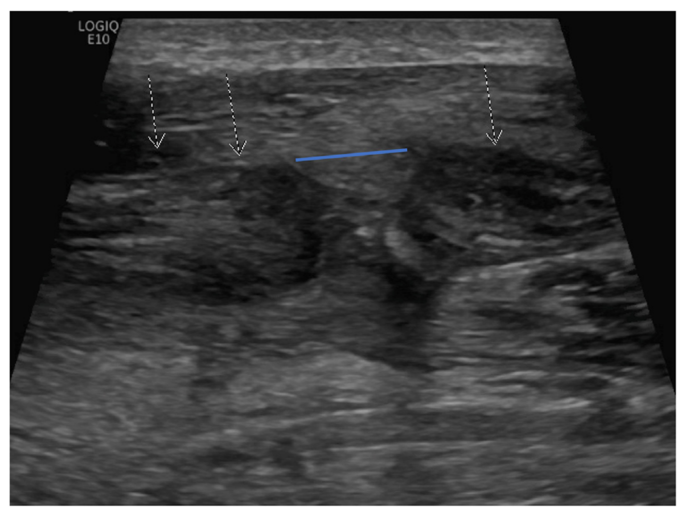

Figure 5. This ultrasound image demonstrates a median nerve not in continuity. This is a clinical image of the median nerve seem in the longitudinal axis from the patient in Figure 2. The arrows represent fascicles of the proximal and distal stumps of the median nerve; however, no fascicles bridging the gap (blue line).

Early exploration (1–2 weeks after injury) allows some time for demarcation of the zone of injury, easier intraneural dissection, and shorter injury gaps compared with delayed exploration. Two cases of ballistic radial shaft fractures with injuries to their median nerves illustrate these points. Both were referred for fracture fixation and nerve repair. One patient had no median nerve or thenar function on examination, whereas the other had some preservation but diminished sensation to light touch in the median nerve distribution. After uncomplicated fracture fixation, both patients were noted to have partial lacerations of the median nerve (Figs. 3 and 4) and underwent sural nerve cabled autograft. In these two cases, early exploration of these nerve injuries allowed for a relatively straightforward intraneural dissection, identification of healthy and injured fascicles, and much shorter grafting than would likely have been required in a delayed injury as seen in the previous cases.

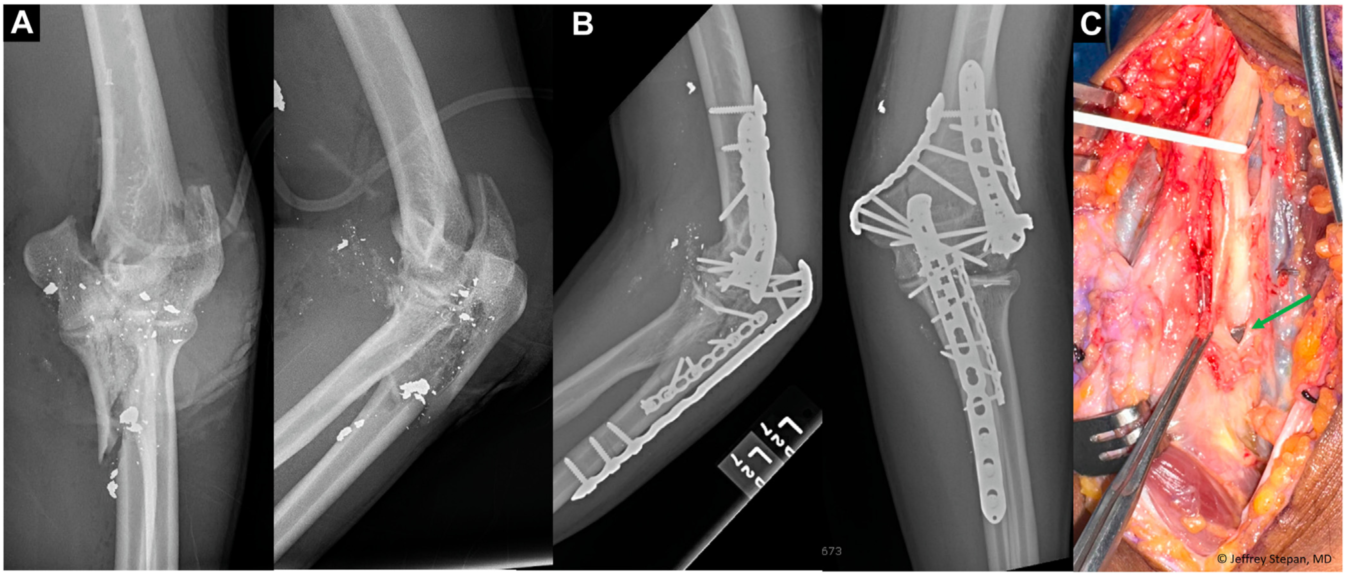

Figure 6. This patient sustained bilateral GSW sustaining a left elbow periarticular injury with decreased sensation in the median nerve distribution and weak but intact anterior interosseous nerve function. The patient also sustained a right ulnar shaft fracture and ulnar nerve injury that underwent an unlar nail and ulnar nerve grafting (not depicted). **A** AP and lateral images of the periarticular ballistic elbow injury. **B** The patient underwent open reduction internal fixation on initial presentation, postoperative images are seen with metallic fragments noted in the anterior soft tissues. **C** The patient eventually underwent median nerve exploration with identification of a metallic fragment embedded within perineural scar tissue likely causing the patient's unremitting pain.

If the nerve is lacerated (often a partial laceration as in the above case), we typically perform acute nerve grafting, given the zone of injury as shown above. We have not encountered a clinical scenario where we have been able to directly repair a nerve with ballistic injury acutely secondary to the large zone of injury encountered, although this has been described. This contrasts with Omer's published findings, which noted that the majority of nerves were repaired primarily with only 19 undergoing grafting (with poor clinical outcome).

Often our trauma, vascular, or orthopedic trauma colleagues will note an injured nerve during their exploration for an acute condition. A 1- to 2-week delay is often sufficient to allow for demarcation in these ballistic injuries, as seen in Figures 3 and 4, where extensive bruising is no longer present.

Some groups have proposed early exploration in all cases, but this is often not logistically feasible in high volume centers. This proposal, based on the available literature, would lead to the many "negative" explorations in patients with intact nerves that would otherwise not require surgery. Recently published literature has shown ultrasound may be helpful in diagnosing nerve injuries, specifically those with severe injuries.[11,12] To help determine the need for early operative intervention, we have introduced ultrasound into our early assessment of nerve injury as an integral part of the work up as soon as feasible. Ultrasound has helped us determine whether fascicles are in continuity or there is a suspected nerve laceration and guide our decision for surgical exploration (Fig. 5). Further research is needed to determine which architectural changes in a grossly intact nerve noted on ultrasound predict clinical recovery.

Unremitting pain can be an indication for exploration

One of the first descriptions of causalgia has been credited to Mitchell et al[13] in 1864 in his work titled "Gunshot Wounds and Other Injuries of Nerves." Here, he discusses the severe pain seen in soldiers shot in the United States Civil War. The following is a description of a soldier with an injured median and ulnar nerve: "He keeps his hand wrapped in rags, wetted with cold water… Moisture is more essential than cold."

As with many other severe nerve injuries, patients' pain can be debilitating, and our pain management colleagues are indispensable in helping with their management. Some patients, however, have pain seemingly out of proportion to their GSW and peripheral nerve injury. Figure 6 presents a case of a patient with bilateral ballistic injuries treated with open reduction internal fixation of his periarticular elbow injury and open reduction internal fixation of the contralateral ulna with ulnar nerve grafting. On the side of the periarticular elbow injury, the patient had unremitting pain despite an examination with intact but decreased sensation in the median nerve distribution and weakness but intact flexor pollicus longus and flexor digitorum profundus to index. Despite being in the early postoperative period from the above surgeries, the patient's main complaint was nerve pain radiating to his hand, which could only be partially relieved with constant tactile feedback of a cup of water (similar to Mithcell's description above). Exploration of the nerve revealed a bullet fragment embedded within the nerve itself. After surgery, the pain improved; however, the patient was subsequently lost to follow-up. A patient's pain severity can be another indicator of nerve injury even when a patient's clinical examination may be underwhelming.

Conclusions and Future Directions

Ballistic nerve injuries are heterogeneous and often do not follow the typical recovery pattern of closed or other open nerve injuries. As more outcomes data become available, we will continue to evolve our treatment protocols.

To summarize our current protocol which is mostly experienced-based, we consider acute nerve exploration (2 weeks) in 1) patients with documented nerve laceration on previous exploration or 2) in the same setting as open reduction internal fixation of a fracture if the nerve injury is in the operative field. At that time, definitive repair or reconstruction can be performed. If an intact nerve is found, we proceed with close follow-up and electrodiagnostic testing at standard intervals.

In patients who present with ballistic nerve injuries without another reason for surgical intervention, we obtain an early ultrasound. Nerve ultrasound, as seen in Figure 5, can help determine if a nerve is grossly intact, analyze fascicular architecture, and determine if there is a partial or complete transection. In cases where the nerve is not intact on ultrasound, I recommend early exploration to reconstruct the nerve prior to a true neuroma in continuity forms. If the ultrasound shows an intact nerve with swelling but intact fascicles, we opt for close clinical follow-up and electrodiagnostic testing. Without return of function at 3 to 6 months, we discuss potential nerve exploration and transfers depending on the location of injury.

Although ultrasound is a promising diagnostic tool, further research is needed into the correlation of intraoperative findings and ultrasound imaging. The appropriate timing of the ultrasound imaging after ballistic nerve injury is also not clear. Future studies should examine how/if certain ultrasound findings can predict the likelihood of nerve recovery in patients with clinical nerve deficits but a nerve in continuity.

Unfortunately, as peripheral nerve and hand surgeons, we commonly see these patients in a delayed fashion 3 to 6 months after injury. There is often a delay by the initial treating surgeon in referring the patient due to this longstanding belief that ballistic nerve injuries will resolve on their own. Educating and communicating with your trauma surgery, vascular surgery, and/or orthopedic trauma colleagues on the importance of early ballistic nerve injury follow-up is vital to the early diagnosis and treatment of these injuries.

Despite this push toward early identification and repair/reconstruction of ballistic nerve injuries, it is ultimately still unknown whether this early intervention will affect clinical outcomes. Outcomes data for ballistic nerve injury remain limited for several reasons. There are a few centers that see high volumes of civilian ballistic nerve injuries, and many patients are lost to follow-up. The only existing data regarding following patients after nerve repair and grafting have shown poor outcomes.[3] Perhaps, it was the delayed treatment or that the zone of nerve injury in ballistic trauma is larger than anticipated that led to these poor outcomes. Although early identification of nerve laceration and nerve reconstruction make surgery technically less demanding and allows for more time for nerve recovery, further studies are needed to demonstrate improved clinical outcomes after these interventions. If early intervention produces similarly poor results, perhaps early distal nerve or tendon transfers may be warranted in the more acute or subacute setting.

Conflicts of Interest

No benefits in any form have been received or will be received related directly to this article.

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