Approach to Complex Upper Extremity Injury: An Algorithm

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Abstract

Patients with complex upper extremity injuries represent a unique subset of the trauma population. In addition to extensive soft tissue defects affecting the skin, bone, muscles and tendons, or the neurovasculature in various combinations, there is usually concomitant involvement of other body areas and organ systems with the potential for systemic compromise due to the underlying mechanism of injury and resultant sequelae. In turn, this has a direct impact on the definitive reconstructive plan. Accurate assessment and expedient treatment is thus necessary to achieve optimal surgical outcomes with the primary goal of limb salvage and functional restoration. Nonetheless, the characteristics of these injuries places such patients at an increased risk of complications ranging from limb ischemia, recalcitrant infections, failure of bony union, intractable pain, and most devastatingly, limb amputation. In this article, the authors present an algorithmic approach toward complex injuries of the upper extremity with due consideration for the various reconstructive modalities and timing of definitive wound closure for the best possible clinical outcomes.

Keywords

- upper extremity
- hand
- trauma
- injury
- algorithm

The anatomy of the upper extremity serves a unique role in the overall function of our daily lives. Beneath the thin layer of enveloping skin is a complex framework of soft tissue elements including bone, and neurovascular and musculotendinous structures that act in concert to allow meaningful exchange with our surrounding environment through both physical and social interactions. The integrity of the overall structure and thus function of the upper extremity can be severely compromised in the setting of complex injuries due to trauma in its various forms such as burns, electrocution, amputation, crush, blast, gunshot, and de-gloving injuries.

However, often the initial insult is not limited to the upper extremity alone and a systemic approach toward addressing the patient in accordance with advanced trauma life support (ATLS) principles is paramount to avoid missing a concomitant life-threatening injury. In short, “life before limb” is prioritized. Antitetanous prophylaxis, if indicated, and intravenous broad-spectrum antibiotics (after wound cultures are taken) should also be initiated expediently according to local institution guidelines for appropriate coverage. Following successful resus-

citation and stabilization efforts with input from orthopedists, and trauma and vascular surgeons, the reconstructive surgeon is then called upon for limb reconstruction and repair of cut structures or for provision of definitive wound coverage (such as after fracture fixation or a guillotine amputation) known as the *orthoplastic approach*¹ to reduce the risks of potential complications including but not limited to osteomyelitis, soft tissue infection, and sepsis. Replantation of a threatened limb is a more urgent situation, which should have priority after treatment of life-threatening injuries, due to the time-sensitive nature of the injury and requirement for emergent intervention. Ultimately, the aim of treatment in complex upper extremity injuries is to preserve the limb and hence restore function, as much as possible, to the patient's premorbid state.²

Initial Requirements

Preoperative

Prior to definitive surgical intervention, it is imperative that several important aspects of the case at hand are carefully

assessed, documented, and considered (► **Table 1**). The time interval prior to presentation will guide the attending physician toward the likelihood of survival especially in situations where replantation of the amputated part(s) is being considered due to the preceding duration and thus extent of tissue ischemia, which should not exceed 8 to 10 hours in the upper extremity.³ The mechanism of injury also provides one with an idea of the extent of tissue damage, wound contamination, and potential functional deficit. Accidents linked to farming or industrial work are more likely to have debris lodged deep within the wounds,⁴ whereas blast or crush injuries and traumatic amputations can severely threaten the viability of the injured upper limb and associated neurovasculature structures. In turn, further workup with an arteriogram may be warranted to both assess the integrity of the vasculature and to prepare for microsurgical reconstruction as well. Although technically feasible, repair of proximal nerve injuries tends to result in less than optimal outcomes due to a combination of factors, including the distance required for axonal regeneration to reach the motor end plate and the complexity of fascicular organization.⁵ An urgent fasciotomy may also be indicated should the clinical suspicion for compartment syndrome be strong and there should be no hesitation in doing so because the morbidity arising from limb ischemia far outweighs that of a potentially limb-saving fasciotomy. Other relevant factors would include whether the dominant limb was involved and what its premorbid functional status was. In addition, existing medical conditions such as poorly controlled ischemic heart disease, diabetes mellitus, and chronic obstructive pulmonary disease may preclude the patient from prolonged anesthesia necessary for extensive reconstructive procedures. Taken together, these various considerations all play a role in the decision to provide definitive soft tissue coverage in an early or delayed manner (► **Table 1**).

Intraoperative

Once the patient has been taken to the operating room for definitive surgical intervention, the injured upper extremity is first irrigated thoroughly to remove as much of the gross contamination as possible; this also facilitates accurate photo-

graphic documentation. A tourniquet is then applied to allow controlled radical debridement of all devitalized tissues. This is the cornerstone of intraoperative management because it prepares the wound bed for definitive closure by converting a contaminated wound into a fresh surgical wound.⁶

In the acute setting (within the first 12–24 h), the wound tends to be necrotic and contaminated due to the circumstances leading to the injury such as tissue trauma and resultant tissue hypoxia. The wound at this stage is approached with en bloc excision starting from the skin edges before extending and moving along deeper tissue planes toward the center of the wound. Care is taken to preserve all viable and longitudinal structures such as blood vessels, nerves, tendons, and bone for functional preservation because a salvaged limb with neither motor nor sensory capabilities is no different from paperweight. All dead, contaminated, and equivocal-looking tissues are removed to decrease the bacterial load in anticipation of wound closure. This is performed in conjunction with careful wound irrigation using copious amounts of solution (normal saline, Ringer's lactate). High-pressure lavage is cautioned against due to concerns over further iatrogenic seeding of the wound bed and collateral damage to vital functional structures in the vicinity.⁷ When all the above has been performed, the tourniquet is released to assess for the adequacy of the debridement. This is evidenced by punctate bleeding and healthy-looking tissue at all levels of the wound. Such debridement may therefore have to be repeated a few of times in the same setting before the surgeon is satisfied with the adequacy of the procedure.

Algorithmic Approach

The provision of a stable bony framework is the next step after debridement because it enables and guides reconstruction of other soft tissues. This should be done at the first surgery or as early as possible to provide a stable skeletal framework for further reconstruction. Fracture fixation can be approached using external fixators with supplementation using Kirschner wires, or through plating for rigid internal fixation. Bone defects are addressed with autografts from the iliac crest, radial shaft, and the fibula depending on the extent of bone loss or through bone shortening as appropriate.⁸ If the patient has other life-threatening injuries and the surgeon wishes to minimize operative time, an external fixator or bridge plate (for distal radius fractures) may be an appropriate treatment modality at the initial surgery. When the patient is more stable, the fixation can be converted to a plate with more attention to anatomical reduction of bone fragments at a subsequent surgery.

Vessels are reconstructed next by trimming proximally to healthy edges before primary, tension-free repair. Undue tension during closure or vascular gaps not amenable to primary anastomosis can be bridged with vein grafts harvested from the saphenous system or by using superficial veins from the dorsum of the hand. Although extensor tendon repairs could be delayed, flexor tendon repairs should be performed in the primary setting if possible or reconstructed using a donor graft such as the palmaris longus in cases of

Table 1 Aspects of upper extremity injury to be considered prior to definitive treatment

1. Time since injury (e.g., duration of ischemia of amputated part)
2. Mechanism(s) of injury (crush, blunt, penetrating)
3. Status of the wound (e.g., contaminated) and field conditions (for amputated parts)
4. Neurovascular status; presence of compartment syndrome
5. Hand dominance and premorbid functional status of the injured upper limb
6. Existing comorbidities (e.g., cardiopulmonary, diabetes) affecting suitability for anesthesia

extensive defects or destruction. Compared with vascular repairs, peripheral nerve reconstruction can be approached with a greater number of options including bridging veins, nerve conduits in the form of silicone or other absorbable materials,⁹ and proximal mobilization for transposition.

Should debridement of the wound be too extensive such that functional reconstruction becomes impossible or suboptimal however, a primary amputation with subsequent prosthesis fitting may be the only option even though the functional and aesthetic results that can be achieved are inferior when compared with limb reconstruction.¹⁰ A similar consideration is employed for replantation cases where the level of amputation, especially at the level of the radius,¹¹ may preclude meaningful functional recovery thereafter. In such situations, application of the “spare parts” concept by utilizing fillet flaps from nonreplantable parts can provide a readily available source of skin and soft tissue for immediate and optimally matched coverage of the amputation stump.¹²

In general, radical debridement in the primary setting is preferred over serial debridement, which is indicated only if the wound cannot be satisfactorily debrided due to severe soiling, or to extensive crush or burn injuries that may only demarcate at a later stage, or in medically unstable patients. The physiological consequences of this deliberate delay are far-reaching when planning for reconstruction. Approximately 3 days after the initial injury, the level of edema and induration of the tissues reaches a peak. Combined with the formation of granulation tissue, tissue planes become less clear and microsurgical anastomosis would then have to be performed even further from the original zone of injury. Immobilization of the injured extremity will further compound the swelling with ensuing joint stiffness and development of tendon adhesions. More importantly, vessels that were otherwise patent have a greater tendency to undergo spasm and thrombosis in response to the preceding traumatic insult. With the buildup of edema fluid, these vessels become coated with fibrin, which then makes for difficult handling during microsurgery in an already challenging situation.

In view of the above, early free flap reconstruction has been strongly advocated by Godina,¹³ Lister and Scheker,¹⁴ and Chen et al,¹⁵ citing additional benefits of shorter overall hospital stays and earlier initiation of rehabilitation for mobilization of the upper limb.¹⁶ However, such dogma has in recent years been challenged by a greater recognition of the utility of vacuum-assisted closure (VAC; Kinetic Concepts, Inc., San Antonio, TX) therapy with increasing advocacy for its use to allow for reconstruction in a delayed setting with no significant difference in reconstructive outcomes reported.¹⁷ Although its exact mechanism of action remains unclear, VAC-treated wounds have been found to be less edematous, to have formed granulation tissue more rapidly for earlier coverage of exposed osseotendinous structures and hardware, and are capable of reducing wound sizes significantly compared with standard dressing therapy.¹⁸ Vacuum-assisted closure therapy also improves blood flow to the wound bed, and in turn enhances antibiotic therapy for eradicating infections.¹⁹ Moreover, this strategy of deliberate delay is in accordance with the principles of damage control

in orthopedics, which aims to avoid the second-hit phenomenon that can jeopardize the reconstruction.²⁰ Finally, the use of VAC therapy can decrease the complexity of reconstruction required from free tissue transfers to local or perforator-based flaps as evidenced by Parrett et al.²¹ Therefore, VAC therapy may prove to be a useful adjunct in cases where the adequacy of debridement is equivocal or if serial debridement is preferred due to reasons outlined previously.

Once the wound bed is deemed ready for closure by the surgeon, either after primary radical debridement or after serial debridement with the adjunctive use of VAC in concert with negative wound cultures, the final extent of reconstruction required will present itself and can normally be addressed using the reconstructive ladder. In most scenarios, the extent of injury will preclude primary closure, but delayed reconstruction with VAC has been demonstrated to decrease both the size of the wound¹⁸ and thus the complexity of reconstruction required.²¹ Local, random pattern, or perforator-based flaps may thus be utilized with the additional benefit of a better tissue match for optimal aesthetics. However, this approach may be limited by the extent of the zone of injury, which may not allow for a local flap option. Regional or distant flaps harvested either proximally or distally from the zone of injury may then be required, but again the choice of flap is limited by pedicle length. Depending on the size, depth, and geometry of the wound bed as well as the extent of involvement of associated structures, free tissue transfers are often most appropriate and can be performed by designing fasciocutaneous, myocutaneous, fascia only, or chimeric flaps to address various issues such as the requirement for dead-space obliteration, resurfacing, coverage for exposed hardware, tendon glide, functional transfers, and simultaneous musculotendinous and nerve repairs.²² Notwithstanding the incredible versatility of free flaps in addressing the multitude of possible defect configurations, it is of utmost importance for the surgeon to have an appreciation for the fine balance between the reconstruction required and further morbidity from donor flap harvest.

► **Fig. 1** summarizes our algorithmic approach to complex upper extremity injuries after debridement.

Postoperative

Depending on the modality of reconstruction, postoperative care may vary from routine wound care in the rare case of primary closure, to the need for extreme diligence in cases where free flap reconstruction was performed. In such cases, care must be taken to protect the pedicle by using loose bulky dressings to avoid unwanted compression, careful splinting with casts to avoid kinking especially where joints are located, and monitoring of the flap according to individual institutional practices for early complications, such as vascular congestion or thrombosis, by looking for clinical signs or with the help of adjuncts such as a bedside Doppler.

The upper extremity is especially prone to the development of stiffness after a period of immobilization. It is thus imperative for the patient to be initiated, as soon as possible, on an individualized rehabilitation program specific to the nature of the injury and subsequent reconstruction (primary

Fig. 1 Algorithmic approach to complex upper extremity injuries after debridement. VAC, vacuum-assisted closure.

or delayed) to prevent the often-seen complications of reduced joint mobility such as edema, tendon adhesions, fibrosis, and scar contractures.²³ Although the goal of early aggressive hand therapy is to prevent or reduce these sequelae, secondary procedures are usually required to resolve these issues due to the priority in providing adequate soft tissue coverage and bony stability in the primary procedure. Various treatment options including bone grafting, corrective osteotomies, capsulotomies, release of scar contractures, delayed nerve reconstruction, neuroma excision, tenolysis or secondary tendon grafting, tendon transfers and functional muscle transfers can be employed, but the underlying principle remains the same: Procedures that require postoperative immobilization should be completed *before* those that should be mobilized early.²⁴ It can be appreciated then that the path to functional recovery of the upper limb is a long and arduous process stretching over a period of months and even years.

Nevertheless, despite the undoubted utility of these procedures and that of an ever-improving array of prostheses,²⁵ hand transplants have now become a clinical reality for patients with various levels of upper extremity amputation or bilateral loss. It remains to be seen whether the “life-giving” procedure of a hand transplant with its attendant risks of chronic immunosuppression can be justified as a treatment option for complex upper extremity injuries not amenable to conventional reconstruction.²⁶

Summary

Complex injuries of the upper extremity seldom occur in isolation and concomitant injuries may have implications on the definitive reconstructive plan. A measure of the success of such reconstruction is not limited to durable soft tissue coverage alone, but rather the extent of functional restoration, including both motor and sensory modalities, of the injured upper limb to allow for successful reintegration of the patient with society. Therefore, such injuries represent a particular surgical challenge. Nevertheless, successful outcomes can still be achieved in such injuries by adopting an algorithmic approach based on the principles of trauma management, adequate debridement for wound bed preparation, and vascularized tissue coverage from outside the zone of injury.

References

- Levin LS. The reconstructive ladder. An orthoplastic approach. *Orthop Clin North Am* 1993;24(3):393–409
- Neumeister MW, Brown RE. Mutilating hand injuries: principles and management. *Hand Clin* 2003;19(1):1–15, v v
- Togawa S, Yamami N, Nakayama H, Mano Y, Ikegami K, Ozeki S. The validity of the mangled extremity severity score in the assessment of upper limb injuries. *J Bone Joint Surg Br* 2005;87(11):1516–1519
- Burkhalter W. Mutilating injuries of the hand. *Hand Clin* 1986;2(1):45–68
- Spyropoulou A, Jeng SF. Microsurgical coverage reconstruction in upper and lower extremities. *Semin Plast Surg* 2010;24(1):34–42
- Scheker LR, Ahmed O. Radical debridement, free flap coverage, and immediate reconstruction of the upper extremity. *Hand Clin* 2007;23(1):23–36
- Hassinger SM, Harding G, Wongworawat MD. High-pressure pulsatile lavage propagates bacteria into soft tissue. *Clin Orthop Relat Res* 2005;439(439):27–31
- Bumbasirevic M, Stevanovic M, Lesic A, Atkinson HD. Current management of the mangled upper extremity. *Int Orthop* 2012;36(11):2189–2195
- Mackinnon SE, Dellon AL. Clinical nerve reconstruction with a bioabsorbable polyglycolic acid tube. *Plast Reconstr Surg* 1990;85(3):419–424
- Graham B, Adkins P, Tsai TM, Firrell J, Breidenbach WC. Major replantation versus revision amputation and prosthetic fitting in the upper extremity: a late functional outcomes study. *J Hand Surg Am* 1998;23(5):783–791
- Prasarn ML, Helfet DL, Kloen P. Management of the mangled extremity. *Strateg Trauma Limb Reconstr* 2012;7(2):57–66
- Brown RE, Wu TY. Use of “spare parts” in mutilated upper extremity injuries. *Hand Clin* 2003;19(1):73–87, vi vi
- Godina M. Early microsurgical reconstruction of complex trauma of the extremities. *Plast Reconstr Surg* 1986;78(3):285–292
- Lister G, Scheker L. Emergency free flaps to the upper extremity. *J Hand Surg Am* 1988;13(1):22–28
- Chen SH, Wei FC, Chen HC, Chuang CC, Noordhoff MS. Emergency free-flap transfer for reconstruction of acute complex extremity wounds. *Plast Reconstr Surg* 1992;89(5):882–888, discussion 889–890
- Hallock GG. The utility of both muscle and fascia flaps in severe upper extremity trauma. *J Trauma* 2002;53(1):61–65
- Harrison BL, Lakhiani C, Lee MR, Saint-Cyr M. Timing of traumatic upper extremity free flap reconstruction: a systematic review and progress report. *Plast Reconstr Surg* 2013;132(3):591–596

- 18 Sinha K, Chauhan VD, Maheshwari R, Chauhan N, Rajan M, Agrawal A. Vacuum assisted closure therapy versus standard wound therapy for open musculoskeletal injuries. *Adv Orthop* 2013; 2013:245940
- 19 Steiert AE, Gohritz A, Schreiber TC, Krettek C, Vogt PM. Delayed flap coverage of open extremity fractures after previous vacuum-assisted closure (VAC) therapy - worse or worth? *J Plast Reconstr Aesthet Surg* 2009;62(5):675-683
- 20 Roberts CS, Pape HC, Jones AL, Malkani AL, Rodriguez JL, Giannoudis PV. Damage control orthopaedics: evolving concepts in the treatment of patients who have sustained orthopaedic trauma. *Instr Course Lect* 2005;54:447-462
- 21 Parrett BM, Talbot SG, Pribaz JJ, Lee BT. A review of local and regional flaps for distal leg reconstruction. *J Reconstr Microsurg* 2009;25(7):445-455
- 22 Neumeister M, Hegge T, Amalfi A, Sauerbier M. The reconstruction of the mutilated hand. *Semin Plast Surg* 2010;24(1): 77-102
- 23 Saint-Cyr M, Gupta A. Indications and selection of free flaps for soft tissue coverage of the upper extremity. *Hand Clin* 2007;23(1): 37-48
- 24 Russell RC, Bueno RA Jr, Wu TY. Secondary procedures following mutilating hand injuries. *Hand Clin* 2003;19(1):149-163
- 25 Kuiken TA, Miller LA, Lipschutz RD, et al. Targeted reinnervation for enhanced prosthetic arm function in a woman with a proximal amputation: a case study. *Lancet* 2007;369(9559): 371-380
- 26 Petruzzo P, Dubernard JM. The International Registry on Hand and Composite Tissue Allotransplantation. *Clin Transpl* 2011: 247-253