

Innovative Techniques for Maximizing Limb Salvage and Function

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Concurrent injuries to multiple extremities present unique challenges to the reconstructive surgeon. The primary goal in such scenarios is to optimize functional outcomes. The goal of this article is to present an overview of various techniques necessary to provide sufficient soft tissue and preserve amputation limb lengths and function. The concept of innovative techniques for maximizing limb salvage and function is presented using an index patient with multiple extremity third- and fourth-degree burn injuries resulting in nonsalvageable lower extremities and severe left-hand wounds. A review of other potential innovative techniques is discussed. The burn injury resulted in a need for bilateral guillotine below-knee amputations. Above-knee amputation was avoided in the left leg using a parascapular free fasciocutaneous flap, while through-knee amputation was preferred to above-knee amputation in the right leg. The preservation of areas with questionable viability resulted in salvaging the left hand of the patient using digital palmar flaps to resurface the dorsum with creation of a first web-space. Maintenance of maximal viable length of limbs and any residual function in the limbs can be of significant functional benefit to multiple limb amputation patients. Maximizing the limb length in such patients is critical, and typical “rules” that have traditionally been utilized to minimize numbers of operations and optimize prosthetic fit may not apply. (J Burn Care Res 2016;XXX:00–00)

Severe limb injuries caused by trauma are a cause of significant morbidity and disability in affected individuals. Such injuries present challenges with regards to reconstruction and rehabilitation, often requiring a multitude of techniques at all levels of

the reconstructive ladder. Therapeutic approaches should be individually tailored to ensure best possible outcomes.

The decision to pursue limb salvage vs limb amputation can be challenging in these patients. Different scoring systems have been established to assist with this decision-making process, but they have demonstrated low sensitivity, and their clinical utilities have not been validated in independent prospective trials.^{1–3} Failed limb salvage efforts can result in morbidity requiring delayed amputation and/or increased mortality.⁴ When considering amputation, surgeons must take into account the ability and morbidity associated with limb salvage, level of amputation, durability of limb/stump coverage, and comorbidities. Other authors have written about the orthoplastic approach to limb reconstruction.⁵ This is never more true than in the multiple limb trauma patient.

The level of the amputation is a key factor in determining the functional outcome of amputation. Typically, a longer amputation stump results in improved postoperative function; this is particularly true when

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a joint can be spared from amputation.⁶⁻⁸ However, the ability to maintain length must sometimes be tempered by the need to fit a prosthesis, which may mount better with a higher level amputation. Fortunately, newer prosthetic fitting techniques are allowing successful lower or through-the-joint fitting.⁹

Unique challenges apply to lower vs upper limbs with respect to the maintenance of length. Lower limb energy consumption is considerably greater with the loss of the knee joint, making below-knee amputations (BKA) considerably preferable in terms of ambulation efficiency.¹⁰⁻¹³ Upper extremities, conversely, do not confer an increasing level of energy expenditure with more proximal level; however, maintenance of length is critical to performing key functions including eating and personal hygiene.

The presence of concurrent injuries may need to be factored into decisions regarding limb salvage vs amputation. The presence of multiple limb injuries adds an additional complexity insofar as each additional limb loss causes an exponential increase in disability. This alters the risk:benefit ratio of complex limb preservation strategies, such as multistaged hand reconstruction. For example, typical nonoperative management of an upper extremity fracture may not be appropriate if this limb will be required for rehabilitation of a concurrent lower extremity injury. Furthermore, the use of spare parts (defined as otherwise discarded autologous tissue) to cover a limb or the ectopic replantation of these spare parts may help to maximize preservation of limb length or coverage.¹⁴⁻¹⁶ In the new era of vascularized composite allotransplantation (VCA—en block transplantation of multiple tissues simultaneously such as a face or extremity), the possibility of downstream limb transplantation must also be considered. For example, a young, healthy transplant candidate who later wishes to undergo VCA will often be best served with the longest stump possible to minimize the distance required for nerve regrowth, and hence the reinnervation of muscles before motor endplate senescence occurs.¹⁷ In addition, maintaining natively innervated muscle (which functions through the pulley mechanism of the transplant tendons) is optimal to avoid the need to innervate donor muscle, which, again, can take considerable time.

The aim of this manuscript is to illustrate the concept and feasibility of maintaining residual limb length and function via multiple plastic surgical techniques in the setting of severe traumatic limb injuries.

Index Patient

The patient, a 30-year-old man, presented with 50% TBSA burns after being extricated from a burning

vehicle after a high-speed motor vehicle crash. He sustained third- and fourth-degree burns to the bilateral lower extremities from the knees down as well the left forearm and left hand, necessitating immediate escharotomies and fasciotomies (Figure 1A, B). This patient was very unwell during much of his treatment primarily related to renal failure and catabolism. We elected to stage surgeries into 2- to 4-hour procedures and separate these by up to a week, meaning that each limb was approached separately. The management of each extremity involving usage of innovative technique is described below. We used temporary xenograft skin coverage but no allograft. We have minimized the usage of allograft to reduce the risk of antibody sensitization, which may complicate future transplantations.

Lower Extremities. Due to marginal patient stability (cardiac arrest requiring Advanced Cardiac Life Support protocol during anesthesia induction) and clear nonviability of the lower legs, below-knee guillotine amputations of both legs were performed on postinjury day 3 since the lower leg muscles were nonviable. Any viable muscle was preserved for later use as coverage. As the patient stabilized, split-thickness skin grafting was performed with thigh donor sites to cover the wounds where possible (Figure 2A). Each leg was then managed separately, tailoring options to the unique but subtle differences at each location.

Right Lower Extremity. The tibia of the right BKA stump was viable, but there was inadequate soft tissue coverage to fashion an appropriate and stable stump for prosthesis fitting. Available options then included converting to an above-knee amputation (AKA) vs using a free flap for soft tissue coverage of the BKA residual limb. A parascapular fasciocutaneous free flap from the left upper back was then performed approximately 4-month postinjury. This was chosen due to the thick and robust skin in this location, which would best tolerate the friction from a prosthesis and would not atrophy to the degree that a muscle flap would. The left side was chosen, as the right shoulder girdle was relatively uninjured and we wished to avoid reducing strength on this side, which would certainly be important for rehabilitation and/or wheelchair use. Microsurgery was challenging due to the wide zone of injury and dissection needed to extend proximally toward the knee using the more intact posterior tibial circulation (Figure 2B, C). Very proximal dissection was also required in order to access viable venae comitantes, which are the veins accompanying the major arteries, due to the more distal destruction of the superficial venous system



Figure 1. Third- and fourth-degree burn of (A) lower and (B) upper extremities.

from the burns and concern for thrombosis of the deep vascular system due to the burn injury.

Left Lower Extremity. The burn injury resulted in a nonviable left tibia with no viable endosteal blood supply and inadequate soft tissue coverage to maintain external vascularity. A BKA with coverage to allow a prosthetic was not possible (Figure 3A), but after extensive discussions with the prosthetic and rehabilitation teams, it was decided that a through-knee amputation (TKA) would be able to be fitted with a prosthesis hinged at the level of the knee, still allowing symmetry to the native contralateral knee joint, but keeping adequate tissues, the patella, and femoral condyles to accept prosthetic loading (Figure 3B). Moreover, it would always be possible to convert a TKA to AKA if these prostheses were ineffective. Again, at the time of TKA 2-month postinjury, all viable muscles were preserved to provide adequate soft tissue coverage after knee disarticulation (Figure 3C).

Left Upper Extremity. The left upper extremity demonstrated clear mummification of the distal fingers with nonviable tissue up to the proximal interphalangeal joints distally and interphalangeal joint on the thumb distally. However, as is common in hand

burns, the palmar skin and circulation were relatively preserved (Figure 4A). Excision of the dorsal soft tissues to the level of the wrist and at the level of the distal interphalangeal joints of thumb, index, long ring, and small fingers was initially performed (Figure 4B). Eventually, all the digits and distal metacarpals on this hand were nonviable, except for the thumb, presumably due to its dual circulation. The maintenance of the viable palmar skin allowed this to be used as a turnover flap to limit the proximal extent of amputation, thus preserving the thumb proximal phalanx and the entire palm and hand (Figure 4C, D). The first web-space was syndactylized to simplify coverage and later released and deepened with dorsal and volar v-shaped flaps and full-thickness skin grafting (Figure 4E, F). This allowed use of this web-space as a dynamic hook and maintained this hand as a “helper hand.” Ultimately, this has also allowed better independent thumb function when using a glove-type prosthesis.

Right Upper Extremity. The burns of the right arm and forearm were full thickness but noncircumferential and measured approximately 500 cm² (Figure 5A). Tangential excisions were performed as compared to faster fascial excisions to preserve

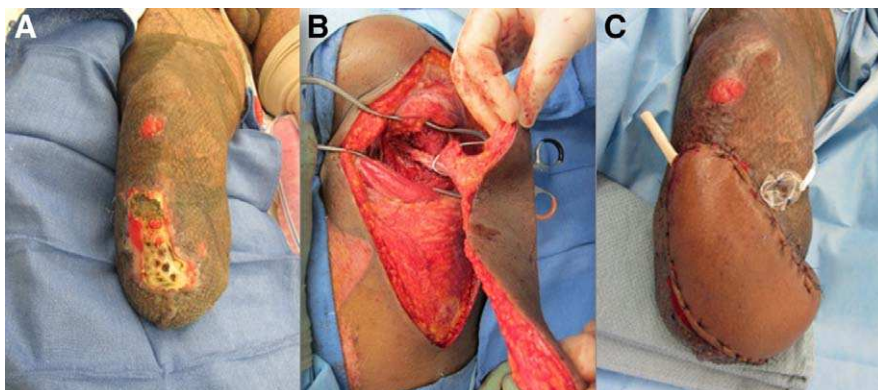


Figure 2. Right lower extremity: A. Original below-knee guillotine stump with split-thickness skin graft, (B) harvesting of free parascapular fasciocutaneous flap, (C) soft tissue coverage of the guillotine stump with parascapular flap.

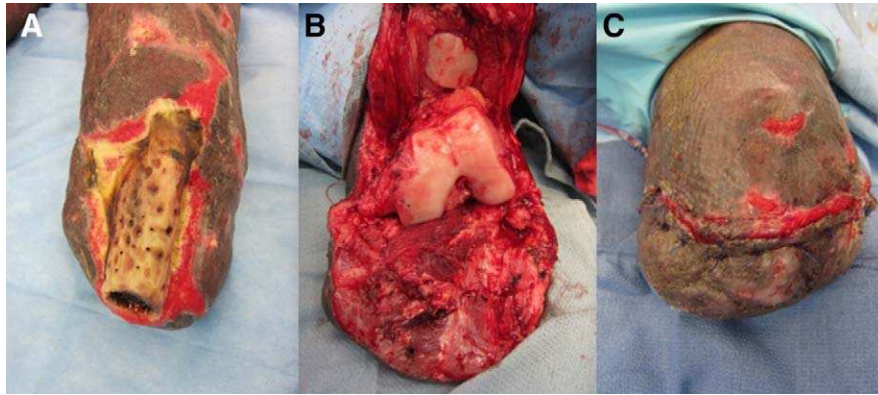


Figure 3. Left lower extremity: A. Exposed below-knee guillotine stump, (B) through-knee amputation, (C) soft tissue coverage of through-knee amputation.

the subcutaneous veins and fat beneath the grafts. Tumescent injection before debridement minimized blood loss, and split-thickness skin grafting was performed from the right thigh 2-month postinjury (Figure 5B). Open reduction and internal fixation of a right humeral shaft fracture and right radial neuroplasty for radial nerve palsy (Figure 5C) were also performed concurrently. In patients with isolated diaphyseal humeral fractures, even in the setting of radial nerve palsy, conservative management with functional bracing is typically favored.¹⁸ In this instance, as is often the case in polytraumatized patients, repair of the fracture facilitated wound and nursing care and allowed for immediate weight bearing and use of the arm for transfers and use of ambulatory aides.^{19,20}

Outcome. After 22 separate trips to the operating room, the patient demonstrated excellent recovery and was able to ambulate independently within 6 months of the initial procedure (Figure 6A, B). He

is currently 56 months out from the last procedure. He is training as a highly competitive sprinter, competing at the Paralympian level. He has not required any additional operations and continues to be functionally independent with activities of daily living, driving, and ambulation.

DISCUSSION

Maximizing functional limb length is critical in multilimb trauma. In this case, we utilized progressive debridement, local flaps, nerve exploration and neurolysis, and collaborative models to determine amputation levels. AKA was avoided in the right lower extremity using parascapular fasciocutaneous free flap using viable venae comitantes, while TKA was used in the left lower extremity to maximize length and optimize prosthetic fitting to a weight-bearing surface. Open reduction and internal fixation of the right humerus allowed faster recovery and

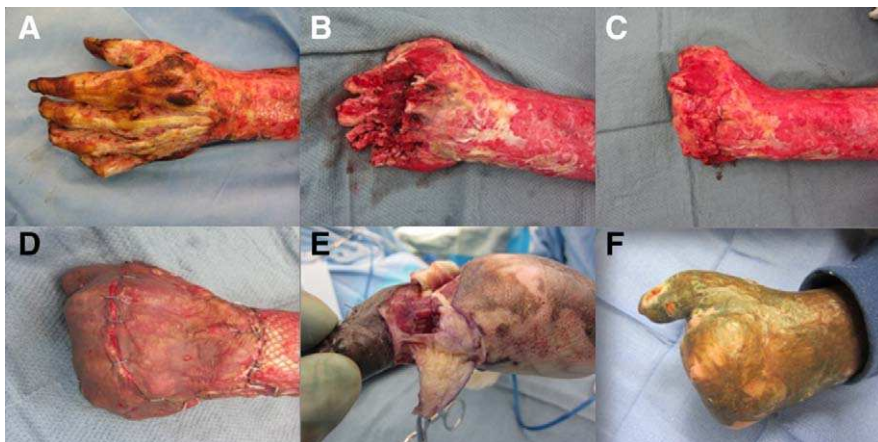


Figure 4. Left upper extremity: A. Debridement of nonviable tissue in the left hand, (B) amputation through distal interphalangeal joints of thumb, index, long, ring, and small fingers, (C) amputation through metacarpophalangeal joints, (D) coverage with volar flap, (E and F) first web-space creation and deepening.



Figure 5. Right upper extremity: A. Full-thickness but noncircumferential burn wounds of right arm and forearm, (B) split-thickness skin grafting after wound debridement, (C) open reduction internal fixation of right humeral shaft fracture.

rehabilitation of the patient. Use of the preserved palmar skin in the left upper extremity enabled preserving the thumb, proximal phalanx, and the entire palm and hand, while open reduction and internal fixation of the right humerus allowed faster recovery and rehabilitation of the patient.

Limb Energy Expenditure Considerations

Longer amputation stump length results in preserving more muscle, bones, and joints, which can increase the range of motion or reach of the amputated stump. In the upper extremity, maintenance of the elbow and at least partial forearm is important to allow access to a wider range of the body, extending to the mouth, face, hair, and trunk to facilitate feeding and hygiene. Furthermore, longer residual limb length provides an increased lever arm, superior mobility, and larger contact surface area, where the inherent forces of prosthetic devices can be

distributed. According to the physics of levers, a longer stump length requires less strength for the same movement; conversely, when the residual stump is too short, greater strength is needed, which limits the overall prosthetic function.

Longer residual limb length and joint preservation have also been shown to decrease an amputee's energy expenditure during functional ambulation in lower limb amputees^{10,11} and are seen as the causative agents for higher walking speeds¹² and greater walking distances⁸ during prosthetic ambulation in BKA patients compared to AKA patients. Converting a BKA to AKA increases energy expenditure from 25% above baseline to 65% above baseline.¹⁰ When a BKA is not possible, amputation at the level of the knee joint offers a satisfactory quality of life while maintaining this length.¹⁰ In AKA patients, the residual femur length substantially influences the patient's energy expenditure, temporospatial, and kinematic gait outcomes. Shorter residual transfemoral length



Figure 6. Six-month follow-up: A. Maintenance of prolonged limb length of amputation stump, (B) independent ambulation with prostheses.

typically consumes more energy and is associated with slower comfort walking speeds.^{12,13} The preservation of residual stump length contributes to the resumption of a more normal gait pattern, increased functional capacity, and decreased energy expenditure.

Through-Knee Amputation

TKA or knee disarticulation in lower extremity amputation is an option relatively rarely used. Advantages compared to AKA include maintenance of stronger muscles, a full-length intact femur, and a longer mechanical lever. The completely preserved thigh muscles offers muscular balance, and the bulbous stump permits total end bearing and an easy prosthetic interface.²¹ TKA has been found by some authors to be a superior alternative from functional and rehabilitation standpoints when compared to AKA,²² and intensive ongoing research activities in designing and improving “through knee prosthetic devices” have further strengthened the argument for TKA.^{23,24} Although TKA was associated with worse sickness impact profile scores and slower self-selected walking scores when compared to AKA in trauma patients,²⁵ the ability to do a prosthesis and use it on a regular basis was also found to be significantly better in TKA patients than in AKA patients.²² Moreover, a recent meta-analysis demonstrated better maintenance of independent living status in TKA patients when compared to AKA patients.²²

Soft Tissue Coverage Options

Soft tissue coverage is often a limiting factor in maximizing the length of a severely injured limb. Significant technical advancements have permitted limb salvage in extreme scenarios and length preservation of amputated extremities by adequately covering and protecting exposed tendons, nerves, bones, and joints.²⁷ The hierarchies of the reconstructive ladder include healing by secondary intention, primary closure, delayed primary closure, split-thickness skin grafting, full-thickness skin grafting, tissue expansion, random flaps, axial flaps, and free flaps. These options can be used individually, in combination, or with multiple variations, and allow complex soft tissue defects to be repaired while maintaining limb length, optimal form, and function. Innovative thinking and avoidance of blindly following rules can often serve to maximize outcomes.

Complex, Free Tissue Transfer

Multiple innovative flap techniques have also been described for extremity reconstruction. If one of the three vessels of the foot is intact, this can be

used to create a “fillet of sole” flap of the foot for coverage of the stump.²⁸ This is particularly true if the posterior tibial artery is intact even if the muscle and nerve injury of the lower leg suggests the need for amputation. Unfortunately, in our patient, the tibial vascular pedicle was so damaged distally that we would have had to trace this very proximally to find enough flow and open veins to support a free flap. Flow-through anterolateral thigh flap for reconstruction in acute electrical burns of the severely traumatized upper extremity provides for reconstruction of both the vessels and soft tissue simultaneously.²⁹ Free vascularized fibular flap combined with allograft for reconstruction of distal third femur defects can increase initial stability, allows early weight bearing, and has a very high chance of union.³⁰ Microvascular free fibula transfer is also considered the most suitable autograft for reconstruction of the middle tibia because of its long cylindrical straight shape, mechanical strength, predictable vascular pedicle, and hypertrophy potential.³¹ They are especially useful in cases of scarred and avascular recipient sites.

Preservation and Use of Spare Parts

Hands demonstrate the key concepts of form and function. With severe hand injury requiring amputation, the key principle is to both restore as much function as possible and save as much of the hand architecture as possible. When tissue viability is questionable, serial debridement (where safe) can maximize the preservation of tissues; partial hands are usually still better than no hands. Also, the judicious use of available tissue that would otherwise be discarded should be considered for facilitating distal reconstruction when routine replantation is not possible. Usage of nonreplantable tissues as “spare parts” to preserve length, obtain soft tissue coverage, and improve the function of less injured portion of the hand can significantly improve outcomes.^{32,33} Using tailored grafts and flaps from adjacent fingers or the feet, replacing like with like, as well as using tissue rearrangement, heterotopic replantation, or ectopic replantation allows the surgeon to maximize function and minimize donor-site morbidity.^{34–36}

Prosthetic Advancements

Advancements in prosthetic design and function are pushing the boundaries of functional outcomes once faced by amputees.³⁷ Improvement in socket design, suspension systems, and aesthetics, combined with the development of activity-specific devices, and microprocessor joints have vastly improved

functional mobility and quality of life for individuals with amputations.^{37,38}

Vascularized Composite Allotransplantation

Advances in immunosuppression and microsurgery have ushered in the era of VCA in both upper and lower extremity restoration.^{17,39–42} Based on the hand transplantation experience, the return of motor function depends on the level of transplantation.¹⁷ Better functional outcomes can be achieved relatively sooner with more distal transplantations, presumably due to the preservation of more native innervated muscle tissue, joints, and less distance for nerve regeneration.¹⁷ In amputees, extrinsic motor function may never be lost when extrinsic muscles and tendons are native to the recipient, and the majority of motion is simply transferred through the “pulley system” of allotransplanted tendons. However, return of intrinsic motor function is dependent on reinnervation of donor muscles.³⁹ In the past, an argument could be made for sacrificing a portion of viable limb in a patient undergoing amputation in lieu of better prosthetic fit during rehabilitation. However, with the promise of VCA as a possible therapeutic option for amputees, prosthetic fit is no longer the cardinal criteria to determine the level of transplantation.³⁹

Other Innovative Techniques

Bioengineered materials also now play an important role in soft tissue coverage. Use of dermal substitutes can be used as a “bridge” to stimulate regeneration in a humid environment in deep burn wounds.⁴³ Dermal regenerative matrices have been described in upper extremity salvage procedure.⁴⁴ We commonly use dermal regenerative matrices but only when vascularized autologous tissue is not available and when there is little demand on the tissues. We avoid this option in places such as for stump coverage, where full-thickness tissue coverage is preferable due to durability. Bone morphogenetic protein has been used for bony regeneration, and bioengineered recombinant parathyroid hormone therapy has shown to have antifibrotic effects on nonunions and critical bone defects, which provides a promising solution for significant clinical hurdles in limb salvage procedures.⁴⁵

Cost–Benefit Analysis

In spite of function being our primary driver, we must be mindful of costs. Studies have shown that 2-year health care costs, accounting for the prosthesis-related expenditure, are significantly higher in lower extremity amputation patients compared with

reconstruction patients.⁴⁶ Projected lifetime health care costs for the patients who have undergone amputation have also been shown to be three times higher than that for those treated with reconstruction.⁴⁶ Maximizing the function of an amputated limb can, to an extent, offset these higher health care costs.

CONCLUSION

Typical “rules” that have traditionally been applied to minimize numbers of operations and optimize prosthetic fit do not always apply. Limb function is a factor of limb length and is the functional part of the prosthesis that restores distal function. Maintenance of maximal length of an amputation stump through multiple approaches such as free tissue transfer, TKA, and usage of spare parts should be considered to maximize the functional outcome.

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