# "Damage Control" Hand Surgery

## Evaluation and Emergency Management of the Mangled Hand

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**KEYWORDS**

• Hand Injuries • Mangled Hand • Hand Reconstruction • Hand Amputation

**KEY POINTS**

- Mangled hand injuries are defined as those with significant damage to multiple structures, which threatens the function and/or viability of the limb.
- The mantra, "life before limb," or a decision to salvage versus amputate must be considered, taking in the overall injury burden when determining surgical options that are best for patients, short term and long term.
- Excessive time without perfusion of the amputated part can lead to irreversible tissue necrosis. Tissue necrosis can at times be obviated if the part is preserved in a cool environment. If ischemia time allows, a common order of fixation includes bone, extensor tendon, flexor tendon, artery, nerve, vein, and skin.
- Post-revascularization, a warm environment (warm room, heating device such as a warming blanket, or both), daily aspirin for 1 month, and intravenous antibiotics for 3 days are recommended.
- Post-revascularization, additional procedures are routine and patients should be prepared in advance for their need.

## INTRODUCTION

Mangled hand injuries are defined as those with significant damage to multiple structures, which threatens the function and/or viability of the limb. Historically, these injuries resulted in death or amputation, but with modern advances in débridement, antibiotics, skeletal fixation, microsurgery, and soft tissue coverage, successful and functional reconstruction of a severely damaged limb is possible.[1] The injury mechanisms resulting in mangling injuries generally are high energy and include either a sharp laceration or a crush/avulsion force. Concomitant disruption of skin, nerves, vessels, bones, joints, tendons, and muscles presents a challenging clinical situation to treating surgeons, who must decide between salvage and amputation. Fortunately, mangling upper extremity injuries are uncommon; only 5% of all

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hand fractures are open and a vast majority of injuries are not limb threatening.[2] As a result of its rarity, however, many trauma centers, including those with American College of Surgeons trauma designation, are not equipped to treat these injuries.

Paramount to treatment of the mangled hand is the mantra, "life before limb." The decision for salvage versus amputation can be difficult; surgeons must consider the overall injury burden and are obligated to consider all options for surgical reconstruction, including the possibility of amputation with prosthetic use. This article discusses the evaluation of the mangled limb, perioperative management strategies, and outcomes.

## INITIAL EVALUATION AND EMERGENCY MANAGEMENT

A patient's first encounter with a health care provider is either at the site of injury or in an emergency department. Depending on the severity of the trauma burden, patients may require standard Advanced Trauma Life Support. In general, the authors recommend against the routine use of tourniquet in the field unless direct pressure does not provide sufficient hemostasis, which is rare.

Appropriate preservation of the amputated or dysvascular extremity is critical. Excessive time without perfusion can lead to irreversible tissue necrosis. Tissue necrosis can at times be obviated if the part is preserved in a cool environment. The authors recommend washing the part to remove debris, then wrapping it in moist gauze. The part is then placed into a plastic bag or container and then placed into another plastic bag filled with ice. Avoid placing the part directly on ice, because frostbite may cause irrevocable injury. The generally accepted limits of warm ischemia are 12 hours for a digit and 6 hours for a more proximal injury,[1] although these are not absolute. Proximal injuries have less tolerance for ischemia due to the higher metabolic requirements of muscle. The ischemic time limits can be doubled for a cooled, well-preserved part.[3] Replantation has been successfully performed as late as 94 hours for a digit and 54 hours for a hand when appropriately preserved.[4,5]

On arrival to the hospital, a few simple steps can greatly assist the treating surgeon and expedite the process of care (**Box 1**). If an upper arm tourniquet is present, it is removed carefully with an understanding of the total ischemia time, patient comorbidities (specifically coronary artery disease and regularity of cardiac rhythm), and the risk of a potassium bolus with reperfusion. Often, the wound is already hemostatic because thrombus has formed at the site of arterial injury. If hemostasis is not controlled, then the authors recommend holding pressure (ideally a single finger over the bleeding vessel) for 10 minutes to control bleeding. A pressure dressing also may be applied. If all techniques fail, then the tourniquet can be replaced knowing that swift transition to the operating room is crucial.

**Box 1**
**Tips for the emergency physician**

- Mind the airway, breathing, circulation (ABCs) first
- Hold firm, focused pressure on bleeding wounds first before applying a tourniquet
- Note pertinent history information
- Perform a focused physical examination
- Carefully note vascular status and place pulse oximeter on all affected digits
- Administer antibiotics
- Inquire tetanus status and treat appropriately
- Irrigate the wound and remove debris
- Cover and splint the limb
- Obtain radiographs and include amputated part within radiographic field
- Ensure the amputated part is properly preserved

A hand and upper extremity surgeon is usually consulted in an urgent fashion for mangled injuries of the hand. If the patient is awake, the surgeon should take a history noting pertinent items related to surgical decision making: age, hand dominance, mechanism of injury, time of injury, comorbidities, medications, occupation, smoking status, tetanus status, method of preserving the amputated part, and patient preferences. Physical examination should include inspection noting deformity and the size, depth, and trajectory of each wound. Palpation can determine the stability of the skeleton and the joints. The patient should then be asked to actively move the affected limb and the digits, which gives insight into nerve, muscle, and tendon function. If the patient cannot move the digits, then using the tenodesis effect (noting extension of the fingers with passive wrist flexion and noting flexion of the fingers with passive wrist extension) can be helpful in determining the integrity of the tendons. A sensory examination should be performed with careful 2-point discrimination in all nerve distributions.

With mangled hands, the vascular examination is critically important. The surgeon should observe

the color of the limb and palpate the digits for temperature and turgor. Capillary refill should be 2 or 3 seconds. Brachial, radial, and ulnar pulses are palpated and graded for strength. If no pulse is present, a Doppler ultrasound should also be used and the palmar arch and the digital arteries should be auscultated. If the perfusion seems inadequate, a pulse oximeter should be placed on the digit; a reading higher than 95% with a pulsatile waveform confirms that the digit is perfused.[6] The authors do not recommend pricking the finger with a needle to observe bleeding; multiple pricks or large bore needles can cause discoloration and/or disrupt critical microcirculation at the tip.

Adjunct laboratory and imaging tests are commonly performed; a complete blood cell count and basic metabolic profile with coagulation parameters are helpful. Radiographs are most useful after the limb has been reasonably aligned (traction view). The amputated part, if present, should also be filmed in the same radiographic field to allow for easy viewing intraoperatively. CT scan can assist surgical planning of fractures but is often not necessary or possible when operative intervention is undertaken emergently.

## OPERATIVE MANAGEMENT

Operative intervention should proceed immediately for a threatened limb. Antibiotics are administered as soon as possible; the authors typically use a first-generation cephalosporin to cover gram-positive bacteria and gentamicin (5 mg/kg every 24 hours) for gram-negative coverage. Penicillin (2–4 million units) is added to prevent clostridium infection if farm or soil contamination is present.

Major limb surgery can be lengthy and complicated; thoughtful preoperative discussion with the surgical and anesthetic team is important regarding the equipment, placement of Foley catheter, patient positioning, use of a leg drape if needed for donor veins and nerves, and anticipated length of surgery. For procedures involving revascularization, the authors prefer placement of a preoperative indwelling catheter to promote vasodilation and assist with postoperative pain. A back table can be invaluable in the setting of amputated parts; it is most efficient to begin identifying and labeling structures on the amputated part at the back table while the remainder of the anesthesia and surgical team is preparing the patient (**Fig. 1**).

The first step in treating a mangled extremity is to carefully assess the damaged structures in a systematic, organized way. The surgeon should be careful not to sacrifice small skin bridges, which may contain intact critical veins for drainage. Large-volume irrigation should be used to remove loose debris, and all devitalized tissue should be sharply removed. Deflating the tourniquet and observing tissue perfusion may assist in determining the viability of tissues. For the skin and soft tissues, this may require resecting skin edges or trimming avulsed tendons or nerves. Poorly perfused muscle should also be removed, because it will form either fibrotic tissue leading to contracture or necrotic tissue leading to infection. Additionally, large segments of devitalized muscle tissue can lead to systemic illnesses, such as hyperkalemia or renal failure from rhabdomyolysis. The 4 Cs—color, consistency, contractility, and capacity to bleed—aid in assessing muscle. Bone fragments that lack soft tissue attachment should be considered devitalized and removed—even if such debridement results in a gap. Sufficient débridement of devitalized tissues is essential in the management of the mangled hand; given its critical importance, it should most often be performed by the most senior member of the surgical team.

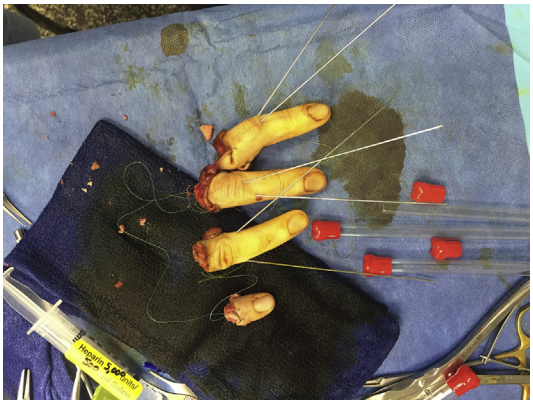

**Fig. 1.** A sterile back table can be useful in improving the efficiency of surgery. In this patient, all 4 fingers underwent débridement, identification of structures, suturing of tendons, bone shortening, and preloaded Kirschner wire fixation. All of this was completed while the operating team was preparing the room and patient.

After débridement, the surgeon should systematically identify all damaged structures and decide whether or not limb salvage will result in a functional and sensate limb; the decision to salvage a digit or limb can be difficult. In general, the authors usually perform salvage if the operation has the possibility of resulting in useful function, but there are times that amputation of a limb (or part) is the most prudent decision. Mangled injuries may result in a stiff, painful, insensate, or functionless limb, which may require extensive therapy and multiple

operations if salvage is undertaken. Although each case is different and should be considered individually, relative indications for amputation (instead of salvage) include a mangled single/border digit, segmental injury, excessive contamination, severe articular destruction, medical instability or comorbidities, perceived lack of compliance with postoperative requirements, self-inflicted injury, and/or prolonged ischemia time.[7]

The art of reconstruction of the mangled hand comes from experience in dealing with these difficult injuries. Surgeons must apply a variety of concepts to create the best extremity possible.

### *Order of Repair*

The nature of injured structures often dictates the order of repair. If an injury is proximal and the distal part (including the intrinsic muscles of the hand) is dysvascular, a vascular shunt may be useful to establish reperfusion and prevent ischemic injury. The authors typically use a 1-mm to 3-mm shunt depending on the caliber of the vessel to be cannulated. Prior to reperfusion, there should be awareness of the possibility of metabolic sequelae of reperfusion, for which the anesthesia team should be prepared. The shunt remains in place until the vascular anastomosis is ready to be performed.

Many mangled injuries to the hand are multidigit injuries, and consideration should first be given to either the part-by-part or digit-by-digit approach. In the part-by-part approach, a surgeon repairs the same anatomic structure of each digit sequentially (first bones and then tendons, vessels, nerves, and so forth). Advantages to this approach include speed and rhythm. Alternatively, in the digit-by-digit approach, the surgeon repairs all structures in each digit sequentially. This may decrease the ischemic time for the prioritized digits. In general, the authors typically use the part-by-part approach with injuries in which the intent is to salvage all digits (because this is most expeditious) and the digit-by-digit approach for injuries in which there are unsalvageable parts and priority must be given to the most important digits for reconstruction.

If the ischemia time allows, a common order of fixation includes bone, extensor tendon, flexor tendon, artery, nerve, vein, and skin. Often, however, the authors' preference is the veins before arteries approach, in which the order of fixation includes bones, extensor tendons, veins, flexor tendons, arteries, nerves, and skin. Performing the venous anastomosis first allows this to be performed under tourniquet control and allows the surgeon to perform the most technically demanding part of the procedure prior to the onset of inevitable technical fatigue at the end of the operation. Additionally, repairing the artery first creates bleeding from the veins, which clouds the operative field and makes an already difficult step more difficult. The order of approach depends on surgeon preference and specifics of the injury.

### *Spare Parts and Heterotopic Replantation*

When planning a reconstruction, surgeons should always consider using the parts of a nonreplantable structure. For example, a nonreconstructible index finger amputation may provide nerve, skin, bone, tendon, or arterial grafts to an adjacent digit. Additionally, priority to replanting the most intact digits should be given to the least damaged amputated fingers (eg, if an amputated index finger is better preserved than an amputated thumb, then the index finger may be replanted to the thumb position to optimize overall function). That is, it is important to use the best remaining structures to create the most functional resultant hand (**Fig. 2**).

Debate exists on the importance of each digit. The thumb contributes approximately 40% of hand function and thus is often given the first priority for reconstruction.[8,9] The radial-sided digits restore precision pinch and chuck pinch, whereas the ulnar-sided digits restore the width of the hand and power grasp.[10] Thus, given the situation, a surgeon may decide to use certain parts of the injured hand. Soucacos and colleagues[11] described 5 indications in which heterotopic replantation is indicated (**Box 2**).[11] The authors' preference is to reconstruct the thumb first followed by the long and ring fingers to provide opposition, pinch, and grasp.

Ectopic replantation is another option for highly damaged limbs in which radical débridement would lead to loss of important structures. Examples include burns, gunshot wounds, segmental trauma, and agricultural inquiries. The first report of ectopic replantation was published by Godina and colleagues,[12] who replanted a hand to the thoracodorsal artery. The hand was transferred to the limb 66 days later after multiple débridements.[12] Other options for ectopic replantation include the groin, axilla, and proximal arm.[13,14]

### *Skeletal Fixation*

Most mangled hand injuries are stabilized by external or internal fixation. In general, the authors prefer internal fixation when possible, because it allows for earlier mobilization and can provide long-term fixation. External fixation can be useful and expeditious in severe injuries and those with gross instability or contamination; placing

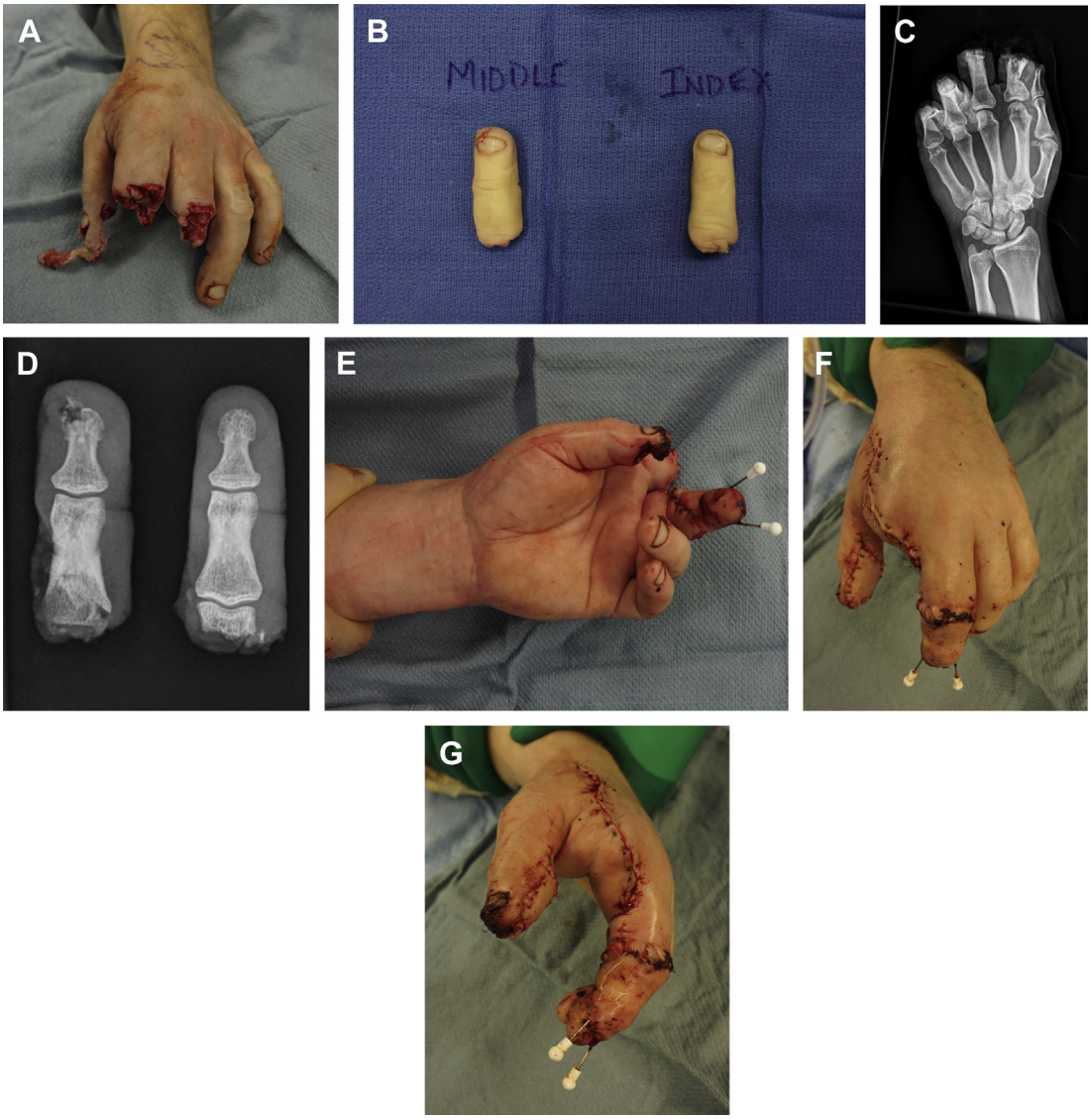


**Fig. 2.** Spare parts can be useful. This patient sustained amputations of the index and middle fingers and a degloving soft tissue injury to the volar aspect of his left thumb (*A*). The index finger amputation level was 1 cm proximal to the proximal interphalangeal joint, and the middle finger amputation level was directly through the proximal interphalangeal joint (*B-D*). The patient underwent heterotopic replantation of the amputated index finger (IF) to the middle finger (MF) position (*E*). He subsequently underwent ray amputation of the index finger with first dorsal metacarpal artery flap reconstruction of the volar thumb defect (*F,G*).

permanent hardware in highly contaminated wounds raises the risk for infection, and medically unstable patients may not tolerate the second trauma of a long operation (damage control surgery).[15]

In the wrist, the authors often use plate fixation with or without percutaneous Kirschner wires; a radial-carpal internal spanning plate (ie, for wrist fusion) can be useful in cases of significant bony injury to the wrist. For the digits, the authors prefer small plates or 90/90 wiring constructs, which provide adequate stabilization. Additionally, the authors usually shorten the bone prior to fixation to relax the tension on the microsurgical vessel and nerve repairs.

If significant bone loss is present, a choice may be to acutely bone graft the defect, possibly from spare parts. Unlike the lower extremity, acute bone grafting in the upper extremity does not seem to have the same risk for infection.[16] Alternatively, if the wound is contaminated, the space may be filled with antibiotic impregnated beads

**Box 2**
**Indications for heterotopic replantation**

1. In a multifinger injury where the thumb is not replantable, the best-preserved digit is transferred to the thumb position.
2. In a bilateral thumb amputation, the dominant thumb is given the best-preserved thumb or digit.
3. In bilateral multidigit amputations, the dominant hand is given the best-preserved digits.
4. In multidigit amputations with an intact thumb, the ulnar-sided positions are given the best-preserved digits to restore grasp.
5. In amputations including all 5 digits, the best-preserved parts are given to restore the thumb first, followed by the ulnar digits.

or a cement spacer, which can later be replaced with cancellous autograft (Masquelet procedure) or structural cortical graft (such as iliac crest).[17] Large segments of bone loss (greater than 6 cm) may benefit from vascularized bone transport or free vascularized bone flaps.[18]

### *Tendon Repair*

Most tendon lacerations can be repaired using standard techniques involving core-locking sutures with an epitendinous running stitch. The authors prefer to run the epitendinous stitch first to avoid bunching and facilitate speed.[19] Most importantly, tendon edges should be débrided of nonviable tissue. Segmental gaps can occasionally be treated with autograft from palmaris longus or from an amputated spare part. If tendon transfers are considered, the authors often perform these in staged fashion after tissue equilibrium has occurred. Large segmental tendon defects or defects in the flexor tendon sheath can be treated in a staged fashion. A silicone Hunter rod can be placed in either the flexor or extensor side to create a sheath for future reconstruction.

### *Vascular Repair*

In the setting of vascular injury, vessel repair is critical to the survival and function of the limb and includes both arterial and venous repair. The technical details of microsurgical anastomoses are beyond the scope of this article, but it is critical for surgeons to adequately prepare and débride the vessels and position themselves optimally for technical success. For dysvascular digits, the authors typically recommend repairing a minimum of 2 digital veins for each artery repaired, which has been correlated with increased survival.[20]

Another important consideration with mangled hand reconstruction is the potential need for a vein graft. Injuries with a crush or avulsion component often require a vein graft because of the extent of vascular injury. The vessel diameter should match the artery, and it is often taken from the volar wrist or the foot/ankle. Larger vessels of the forearm may require harvesting the greater or lesser saphenous vein. For injuries involving the arch, vein grafts with a reversed Y configuration can be harvested, often from the dorsal foot, to reconstruct the common digital arterial branches.

Microsurgical repair can fail for numerous reasons. (1) If the repair is performed on an injured vessel, the surgeon must evaluate the vessel under the operating microscope and débride proximal and distal vessel ends to an uninjured segment. Parts that appear kinked (ribbon sign) or bruised (red line sign) should be resected. Adequate débridement is confirmed by observing robust, pulsatile blood flow from the proximal segment. (2) Failure can also occur from technical error, which should be immediately recognized and remedied. (3) Microvascular failure can also occur from infection, which causes vasoconstriction and thrombosis. (4) Failure can occur from excessive extrinsic compression. To avoid compression, the authors perform fasciotomies for proximal injuries, a loose skin closure to allow egress of blood or serous fluid, liberal use of skin grafts, and loose dressings with nothing in between the fingers. (5) Failure can occur from inadequate venous outflow; congestion causes a reduction in inflow followed by necrosis.

### *Nerve Repair*

A perfused limb or digit without sensation is not functional. Nerve repair in the setting of a mangled limb is often performed near the end of the procedure but often is one of the more important parts of surgery. Lacerated or avulsed nerves should be débrided back to healthy fascicles under the microscope. This can be confirmed by palpation of the nerve ends, visualization of pooching fascicles, and the presence of endoneurial bleeding. A tensionless repair should be achieved, or alternative methods of neurrorhaphy should be used (ie, conduit, allograft, or autograft repair). When a nerve gap is present, a small gap (<10 mm) can be bridged with a nerve conduit[21] whereas larger nerve gaps should often be bridged with allograft or autograft.[22] Generally speaking, it is

the authors' practice to perform nerve repair or reconstruction at the time of the initial surgery regardless of the method required.

### *Soft Tissue Coverage*

Soft tissue coverage should be considered at the time of initial evaluation, because this is an important aspect of recovery and paramount to allow for gliding of critical structures. Most often, primary closure is possible and is the first choice. It is important to close the skin loosely to allow for drainage and egress of fluid.

If primary closure is not possible, healing by secondary intention is another option and may be appropriate in small defects. Other times, skin grafting may be sufficient for coverage but generally is inadequate over bone devoid of periosteum or tendon without paratenon.

For larger defects, temporary coverage with Integra or a negative pressure wound device may be the best option for initial management. In the authors' experience, larger defects commonly require flap coverage and the preference is to perform this within 1 week postinjury, assuming the wound is sufficiently clean and adequately débrided. Early soft tissue coverage for mutilating injuries has been shown in studies to decrease late infection.[23] A variety of local, regional, and free flaps exist for this purpose (**Table 1**). Definitive flap coverage may occur acutely or as part of staged protocol when a wound is clean and fully débrided. In the current era of routine microsurgery, it is the authors' opinion that free flap

**Table 1**
**Common flaps for upper extremity reconstruction**

| Flap | Dominant Vessel | Destination |
|---|---|---|
| V-Y advancement | Random | Transverse or dorsal oblique finger tip |
| Rotational | Random | Dorsal hand or forearm |
| Cross-finger | Random | Volar finger |
| Thenar | Random | Finger tip |
| Moberg | Thumb digital arteries | Volar tip of thumb |
| First dorsal metacarpal artery | First dorsal metacarpal artery | Dorsal or volar thumb |
| Posterior interosseous artery | Posterior interosseous artery | Dorsal hand or forearm |
| Reverse radial forearm | Radial artery | Volar hand, web space, dorsal hand |
| Reverse lateral arm | Posterior radial collateral artery | Elbow or free flap to cover hand or forearm |
| Groin | Superficial circumflex iliac artery | Hand or forearm |
| Abdominal | Medial or lateral row perforators of deep inferior epigastric artery | Hand or forearm |
| Anterolateral thigh | Descending branch of lateral femoral circumflex artery | Free flap to cover hand or forearm |
| Gracilis | Branches of medial femoral circumflex | Free-functioning muscle transfer with neurorrhaphy to obturator nerve for forearm or arm |
| Latissimus dorsi | Thoracodorsal artery | Pedicled or free flap to cover the upper extremity |
| Fibula | Peroneal artery | Free osseous flap for bony defects in the arm or forearm |
| Medial femoral condyle | Descending genicular artery | Free flap for osseous defects in the forearm or hand |
| Great toe | First dorsal metatarsal artery (from dorsalis pedis) or plantar digital artery (from lateral plantar artery) | Free flap for thumb or finger reconstruction with digital nerve and tendons |

coverage is, at times, the safest and most expeditious way to cover difficult wounds, and sacrificing the anterograde radial (or ulnar) arterial inflow is rarely chosen.

## POSTOPERATIVE MANAGEMENT

The limb should be placed in a loose dressing, usually involving a plaster splint, and elevated. Patients with heavily contaminated wounds may require repeat débridement within 24 hours to 48 hours. It is imperative to débride all nonviable tissue prior to definitive coverage.

For those patients undergoing revascularization, the authors use a warm environment (warm room, heating device such as a warming blanket, or both) and daily aspirin. Most often, the authors do not use adjunctive anticoagulants, such as heparin, enoxaparin, or dextran, unless there is a clinical reason to do so. Monitoring for perfusion usually occurs every hour for the first 24 hours postoperatively, which consists of continuous pulse oximetry on 1 or more of the digits and evaluation of skin color, turgor, capillary refill, temperature, and Doppler pulse. Arterial insufficiency is heralded by pallor, flaccid turgor, slow refill, cool temperature, reduced oximetry, and absent pulse. Venous insufficiency is heralded by violaceous color, engorged tissues, brisk capillary refill, low temperature, and low or normal oximetry reading, often with a present pulse. Some of these features can be difficult to distinguish in individuals with darker skin (Fig. 3), and it is critical to have experienced nursing for care of these patients.

Arterial insufficiency requires immediate exploration if an attempt at salvage is to be made; the surgeon is required to evaluate the anastomosis and repair or vein graft the segment if thrombosis is present. Venous insufficiency can, at times, be treated with controlled bleeding with either leech therapy or rubbing the nail bed periodically with a heparin-soaked pledget. If leeches are used, antibiotic prophylaxis with ciprofloxacin is added to cover *Aeromonas hydrophila*. In general, the authors return to the operating room immediately for vascular issues after proximal extremity injuries and thumb revascularization but are more selective with single digits, particularly if there are multiple injured components.

Intravenous antibiotics are continued for 48 hours to 72 hours after the last débridement. In general, the authors usually begin some form of passive motion therapy and splinting before discharge; however, this is dependent on the injury and the restrictions on tendon gliding and early motion. Patients usually remain on an aspirin for 1 month. The first postoperative visit occurs within a week of discharge and focuses on wound care, soft tissue viability, and motion. At this visit, it is important for patients to understand the nature of their injuries and the expectations and requirements for recovery.

In patients with mangled upper extremity injuries, secondary procedures are often necessary. Tenolysis and capsulotomy are the most common secondary procedures usually occurring in the first 3 months to 6 months. Other considerations include reconstructive options for additional soft tissue coverage, bone loss or nonunion, tendon transfers, nerve grafting or transfers, toe transfers, and vascularized composite allotransplantation.[24] Secondary procedures are tailored to a patient's functional needs and wishes for additional intervention.

## OUTCOMES

Outcomes are difficult to assess due to the vast heterogeneity of injuries. Scoring systems have emerged based on pain, motion, sensation, ability to work and care for oneself, and patient satisfaction.[25,26] For replanted digits, survival rates are reported between 57% and 92%.[26–36] Favorable factors for survival include well-preserved part,


**Fig. 3.** Examples of vascular insufficiencies. (*A*) Arterial insufficiency. (*B*) Venous insufficiency. (*C*) Insufficiency highlighting the difficulty in dark-pigmented individuals.

sharp injury, radial-sided digit, no history of tobacco use, and no concurrent life-saving surgery.

With appropriate salvage, outcomes can be good. Finger replantation was shown in a review by Hattori and colleagues[30] to have superior appearance and function compared with amputation. Graham and colleagues[31] reviewed amputations proximal to the wrist and found superior functional scores with replantation compared with revision amputation/prosthetic fitting. Function seems to correlate with the mechanism of injury, the level of injury, severity of injury, and ischemic time. Range of motion is usually greater in amputation levels outside of flexor tendon zone 2. Paavilainen and colleagues[32] reported on transmetacarpal replantations that measured a final average total arc of motion of 154° with the mean grip and pinch strength measured at 56% and 58% of the unaffected side, respectively. Sears and Chung[33] reported an average total arc of motion of 174° in finger avulsion injuries. The functional outcomes of proximal limb replantation are significantly inferior compared with distal injuries. Hierner and colleagues[34] reported that a "functional" upper extremity could be reconstructed in 25% of upper arm replantations, 30% of proximal forearm replantations, and 58% of distal forearm replantations. Recovery of sensibility is more favorable for younger patients, sharp injuries, and distal injuries; in a series of 400 digital replantations, Glickman and Mackinnon[35] noted an average 2-point discrimination of 8 mm in sharp amputations and 15 mm in crush avulsion injuries.[35]

In conclusion, although a variety of factors may alter the outcome, reasonable expectations of limb salvage include approximately 75% to 80% survival, half the strength and motion of the unaffected side, and recovery of protective sensation in most distal injuries. If done well, patients can achieve superior function and are grateful with upper extremity limb salvage. Patients should understand that longer recovery, risk, cost, and multiple procedures, however, are usually required to achieve that goal.

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