Soft-Tissue Injuries Associated With High-Energy Extremity Trauma: Principles of Management

Brent L. Norris, MD, and James F. Kellam, MD

Abstract

The management of high-energy extremity trauma has evolved over the past several decades, and appropriate treatment of associated soft-tissue injuries has proved to be an important factor in achieving a satisfactory outcome. Early evaluation of the severely injured extremity is crucial. Severe closed injuries require serial observation of the soft tissues and early skeletal stabilization. Open injuries require early aggressive debridement of the soft tissues followed by skeletal stabilization. Temporary wound dressings should remain in place until definitive soft-tissue coverage has been obtained. Definitive soft-tissue closure will be expedited by serial debridements performed every 48 to 72 hours in a sterile environment. Skeletal union is facilitated by early bone grafting and/or modification of the stabilizing device. Aggressive rehabilitation, including early social reintegration, are crucial for a good functional outcome. Adherence to protocols is especially beneficial in the management of salvageable severely injured extremities.

J Am Acad Orthop Surg 1997;5:37-46

High-energy extremity injuries are commonplace in our fast-paced and violent modern world. Orthopaedic surgeons must promptly assess, accurately diagnose, and appropriately manage these injuries. Fracture (hard-tissue trauma) is recognized as the major component of most of these injuries. However, all injured extremities will exhibit a component of soft-tissue trauma, usually severe in nature. The soft-tissue trauma is the more important injury, dictating the initial and sometimes definitive management of the traumatized extremity. Furthermore, a good soft-tissue envelope is crucial to fracture healing and overall extremity function. For these reasons, understanding and appreciating the complexity of the soft-tissue injury is paramount for determining the appropriate management of the traumatized extremity.

Several factors are responsible for the evolution of management of soft-tissue injuries associated with fractures. The advent of regional trauma centers has concentrated clinical experience with high-energy injuries as well as the resources for dealing with them. This has led to the development of classification schemes and protocols that now guide medical and surgical management. In this review, we will discuss classification schemes and management protocols for the severely injured extremity and address some of the specific techniques used in the treatment of soft-tissue injuries associated with high-energy extremity trauma.

Classification

Principles

The purpose of any classification scheme is to accurately describe similar events or injuries so as to provide a basis for choosing treatment, estimating prognosis, and allowing comparison. To do so, the individual components that constitute the event or injury being observed must be identified. Brumback[1] has effectively described the components of an open tibial fracture, which can be applied equally well to the assessment of any traumatized extremity. Careful assessment of the following components allows an accurate description: (1) history or mechanism of injury; (2) vascular status of the extremity; (3) size of the skin wound; (4) muscle crush or loss; (5) periosteal stripping or bone necrosis; (6) fracture pattern, fragmentation,

Dr. Norris is Orthopaedic Trauma Fellow, Department of Orthopaedic Surgery, Carolinas Medical Center, Charlotte, NC. Dr. Kellam is Vice Chairman, Department of Orthopaedic Surgery, Carolinas Medical Center.

Reprint requests: Dr. Kellam, Department of Orthopaedic Surgery, Carolinas Medical Center, PO Box 32861, Charlotte, NC 28232.

and/or bone loss; (7) contamination; and (8) compartment syndrome.

Some of the components of the injury to the traumatized extremity can be elucidated immediately; others require evaluation at the time of initial debridement, subsequent debridement, or even later. Therefore, no single assessment is adequate, and continual reevaluation of the "personality" of the injury is required. Brumback[1] and others believe that it is simply impossible to accurately describe a traumatized extremity before surgical debridement. Brumback also implores the orthopaedic surgeons treating traumatized extremities to remember the following axiom: "As the energy exerted to an extremity increases, so does the severity of the multiple components of that injury. Although these components must be individually assessed, their sum represents the 'personality' of the particular injury."[1]

Classification Schemes

In 1976, Gustilo and Anderson[2] described the classification system for open fractures that is the basis for the system currently used by most American orthopaedic surgeons. The purpose of the classification system was to define treatment protocols for various open fractures so as to combat the high infection rates associated with these injuries. In their original study, three types of open fractures were identified. Type III fractures were those with severe soft-tissue injury, segmental fracture, and/or traumatic amputation. All fractures were treated with prophylactic antibiotics, early debridement, and copious irrigation. Type I and II fractures were closed primarily, and type III fractures were closed secondarily. Infection rates were reduced, prompting the use of this classification and treatment protocol for many years.

In 1984, Gustilo et al[3] amended the classification scheme on the basis of the variable results obtained with type III fractures (Table 1). Type III open fractures were subdivided into types IIIA, IIIB, and IIIC. The original classification scheme for type III fractures was too inclusive. It did not account for the variability of severe soft-tissue injury, contamination, fracture instability, and compromised vascularity, all of which are important components to consider when assessing a traumatized extremity. The modified Gustilo-Anderson classification system incorporates these factors in order to further stratify traumatic injuries to the extremities.

Despite the improvements in the Gustilo-Anderson system, a recent study by Brumback and Jones[4] showed poor interobserver reliability between orthopaedic surgeons treating traumatized extremities. These authors emphasized the subjectivity that is inherent to this classification scheme. Although many orthopaedic surgeons still use this system, the search for a better classification scheme continues.

In the early 1980s, Tscherne et al devised a classification system for fractures based on the soft-tissue injury (Table 2).[5] Closed fractures were divided into four types (grades 0 through 3), and open fractures were divided into four types (grades 1 through 4). The grade 3 closed fracture is characterized by extensive muscle damage, vascular injuries, and/or compartment syndrome. The grade 4 open fracture is defined as an amputation. Any revascularization or attempt at limb salvage makes the injury grade 3. This system is currently the most widely accepted classification scheme in Europe. The utility of this system resides in the fact that the individual components of the soft-tissue envelope are described. In addition, closed fractures with severe soft-tissue injury can be classified for treatment, and eventual prognosis can be estimated.

Table 1
Modified Gustilo-Anderson Classification*

Type I	Open fracture with a clean wound <1 cm long
Type II	Open fracture with a laceration >1 cm long without extensive soft-tissue damage, flaps, or avulsions
Type III	Open segmental fracture, open fracture with extensive soft-tissue damage, or traumatic amputation
Type IIIA	Extensive soft-tissue laceration with adequate bone coverage, segmental fractures, gunshot injuries (including low-velocity wounds)
Type IIIB	Inadequate soft-tissue coverage over bone
Type IIIC	Arterial injury

* Adapted with permission from Gustilo RB, Mendoza RM, Williams DN: Problems in the management of type III (severe) open fractures: A new classification of type III open fractures. *J Trauma* 1984;24:742-746.

Table 2
Tscherne Classification*

Closed tibial fracture	
Grade 0:	Closed fracture, no soft-tissue injury
Grade 1:	Indirect injury, contusion from within, superficial laceration
Grade 2:	Usually direct injury with deep contaminated abrasion or severe indirect injury with significant blistering and edema; impending compartment syndrome
Grade 3:	Usually direct injury with extensive contusion or crushing; muscle damage may be severe; vascular injury or compartment syndrome
Open tibial fracture	
Grade 1:	Skin lacerations through a bone fragment from inside, little or no contusion of skin
Grade 2:	Any type of skin laceration with circumscribed skin or soft-tissue contusion and moderate contamination; can occur with any type of fracture
Grade 3:	Fracture must have severe soft-tissue damage, often with major vessel and / or nerve injury; all fractures accompanied by ischemia and severe bone comminution belong in this group, as well as those due to farming accidents and those associated with compartment syndrome
Grade 4:	Subtotal and total amputation, defined as separation of all important anatomic structures, especially major vessels with total ischemia; remaining soft tissue may not exceed one fourth of circumference of extremity (any revascularization is grade 3)

*Adapted with permission from Müller ME, Allgöwer M, Schneider R, et al: *Manual of Internal Fixation*, 3rd ed. Berlin: Springer-Verlag, 1991, pp 152-157.

The AO / ASIF group has added a soft-tissue classification to its extensive fracture classification (Table 3). Three components of the soft-tissue envelope—the integument, the muscles and tendons, and the neurovascular bundle—are graded separately on a scale of one to five, with five being the most severe injury. Injuries to the integumentary system are subdivided into five closed grades and five open grades. The combinations of the three component grades make up the soft-tissue classification. With the use of this system, an extremity injury can be precisely stratified. An advantage is that like injuries will be stratified similarly, allowing better and more consistent evaluation of treatment protocols. A disadvantage, as with the AO fracture classification, is that the system seems overwhelming at first glance. In reality, however, grading is quite simple, as it is only a descriptive report of the injury, which can later be categorized for computer use.

Predictive Indices

The appropriate management of patients with massive extremity trauma is a subject of considerable controversy. Changes in the health-care system in the United States have created additional pressure because of the demand for cost-effective care with proven acceptable outcomes. Recent advances in management techniques have made salvage possible after the most severe and complex injuries. It must be remembered, however, that limb salvage sometimes leads to prolonged and highly morbid functional deficits.

In an attempt to better identify high-energy extremity injuries that are beyond salvage, several classification systems and predictive indices have been devised to assist the orthopaedic surgeon in decision making. The Mangled Extremity Severity Index (MESI), the Predictive Salvage Index (PSI), the Mangled Extremity Severity Score (MESS), and the Limb Salvage Index (LSI) are just a few of these systems. Each system yields a predictive index or score for the severely traumatized extremity (Table 4).

Bonanni et al[6] and others[7] have shown that these indices are not a substitute for clinical judgment. These studies address the deficiencies of each system, including poorly defined injury criteria, cumbersome application, retrospective data, small numbers, little functional outcome data, and inflated accuracy.[6,7] The reader is referred to the article on mangled extremities by Dirschl and Dahners[8] in the July / August 1996 issue of the *Journal of the American Academy of Orthopaedic Surgeons* for an in-depth review of the value of predictive indices.

The goal of therapy in all patients with severely traumatized extremities is the restoration of near-normal function with minimal morbidity in a reasonable time interval. The morbidity arises from prolonged salvage attempts, and guidelines are needed to prevent the morbidity of late amputation and nonfunctionality of salvaged limbs. In all predictive schemes, the only consistent element is the degree of muscle damage. This correlates with clinical

Table 3
AO/ASIF Soft-Tissue Classification*

Integumentary injury (I)
- Closed (C)
  - No skin lesion (IC1)
  - Contusions but no skin laceration (IC2)
  - Circumscribed degloving (IC3)
  - Extensive closed degloving (IC4)
  - Necrosis from contusion (IC5)
- Open (O)
  - Skin breakage from inside out (IO1)
  - Skin breakage from outside in <5 cm, contused edges (IO2)
  - Skin breakage >5 cm, increased contusion, devitalized edge (IO3)
  - Considerable full-thickness contusion, abrasion, extensive open degloving, skin loss (IO4)

Muscle / tendon injury (MT)
- No muscle injury (MT1)
- Circumscribed muscle injury, one compartment only (MT2)
- Considerable muscle injury, two compartments (MT3)
- Muscle defect, tendon laceration, extensive muscle contusion (MT4)
- Compartment syndrome / crush syndrome with wide injury zone (MT5)

Neurovascular injury (NV)
- No neurovascular injury (NV1)
- Isolated nerve injury (NV2)
- Localized vascular injury (NV3)
- Extensive segmental vascular injury (NV4)
- Combined neurovascular injury, subtotal and total amputation (NV5)

*Adapted with permission from Müller ME, Allgöwer M, Schneider R, et al: *Manual of Internal Fixation*, 3rd ed. Berlin: Springer-Verlag, 1991, pp 152-157.

Table 4
Index Variables for Predicting Outcome Scores*

Variables	MESI	PSI	MESS	LSI
Skin / muscle injury	+	+	+	+
Bone injury	+	+	+	+
Ischemia	+	+	+	+
Vascular injury	+	+	–	+
Nerve injury	+	–	–	+
Shock	+	–	+	–
Age	+	–	+	–
MOI	+	–	+	–
ISS	+	–	–	–
Comorbid disease	+	–	–	–

*Abbreviations: ISS = injury severity scale score; MOI = multiplicity of infection; + = provides useful information; – = does not provide useful information. Adapted with permission from Bonanni F, Rhodes M, Lucke JF: The futility of predictive scoring of mangled lower extremities. *J Trauma* 1993;34:99-104.

outcome with respect to healing, infection, and function. The greater the muscle loss, the poorer the result.

When absolute indications for primary amputation are not met, guidelines are needed to discern which extremities will be nonfunctional or will eventually require amputation. Developing predictive criteria is the ultimate challenge. Until strict numeric predictors are available, decisions should be based on clinical impressions and the careful assessment of the traumatized extremity.

Management

Initial Assessment

The first priority when evaluating a patient with a high-energy extremity injury is to determine whether that or any other injury is life-threatening. The concurrence of head, chest, abdominal, and pelvic injuries is common. The survival of the patient is the ultimate goal, and limb injury, even if limb-threatening, must be kept in perspective.

When the immediately life-threatening conditions have been managed, the patient should be evaluated for limb-threatening injuries. After the patient has been adequately resuscitated, the management of a severely injured extremity begins with assessment of its viability. The vascular integrity is determined by clinical examination of the pulses, color, and capillary refill and, when indicated, by Doppler assessment of the ankle-brachial index (>0.9 is normal) and / or arteriography. The other components of the soft-tissue injury are then evaluated in a systematic fashion, including the history and mechanism of injury, the size of the injured area, the type of trauma (e.g., shear, crush, laceration), the fracture pattern, and the presence of periosteal stripping, bone necrosis, contamination, or compartment syndrome. Analysis of these components must be viewed as a progressive process. Some will be apparent at presentation. Others will be elucidated at the time of initial debridement. Several reassessments may be needed to discern compartment syndrome. Therefore, no single evaluation is sufficient to delineate the personality of the severely traumatized extremity.

After the initial assessment, the decision-making process begins. The injured extremity is only one aspect of polytrauma, and the orthopaedic surgeon must therefore coordinate the management plan with the trauma team. Prompt surgical intervention is vital in treating the severely injured extremity, but the goals of the trauma team take priority and may necessitate modification of the surgical plan for the traumatized extremity.

Goals of Treatment

The goals of treatment of the high-energy extremity injury are simple: to prevent infection and to preserve or restore function. The achievement of these goals is anything but simple. The prevention of infection is multifactorial and requires a coordinated treatment plan for fracture stabilization and soft-tissue coverage. The preservation and restoration of function are often extremely difficult to achieve because of the presence of nerve and muscle injury, ischemia, and compartment syndrome. Early surgical intervention is aimed at treating these potentially devastating events. Coordination of the reconstructive procedures and rehabilitation of the injured muscle are also imperative if maximum function is to be obtained.

Preventing Infection

Debridement

A clean wound is the goal of surgical treatment. There is no substitute for early aggressive surgical debridement followed by copious irrigation. Before undertaking debridement, a tourniquet should be placed around the involved extremity but should not be inflated unless exsanguinating bleeding is encountered. The patient can then be properly positioned on the operating table so as to allow access to the entire area of injury.

A sterile field is necessary before initiation of the formal debridement. Use of a "double setup" (separate sterile preparations for debridement and stabilization) has been recommended by several leading orthopaedic trauma surgeons; however, no prospective study supports this practice. Nevertheless, it is our opinion that use of a double setup decreases the risk of infection, and this technique is currently used at our institution.

Superficial and deep exposure of the zone of injury is necessary for adequate debridement. This will necessitate planning the definitive fracture-stabilization procedure before commencement of the formal debridement so that extension of the open wound will allow adequate visualization of all devitalized tissue but will not compromise fixation or viable soft tissue. When extending open wounds, attention to surgical technique is important so as not to further traumatize marginally viable tissue. The tourniquet should be left deflated to discern whether the tissues being evaluated are viable. Nonviable skin should then be excised, leaving a fresh bleeding skin edge. The current trend is toward less aggressive skin excision and more aggressive excision of nonviable deep tissue. The determination of muscle viability still relies on the "four C's": consistency, color, contractility, and circulation.

All viable tissues in the zone of injury should be retained and reevaluated at another scheduled debridement. Marginally viable tissue can be retained and reevaluated at a second debridement if the zone of injury is small. Large areas of marginally viable tissue will usually require excision. Debridement must be meticulous and complete to remove all devitalized tissue, including large bone fragments if they lack blood supply. Debridement must be carried out until normal tissue is seen. Only after a thorough debridement has been performed should attention be turned to irrigation.

Irrigation

It is widely accepted that thorough and copious irrigation of contaminated wounds will lower the risk of infection. However, the optimal type and volume of irrigant and method of administration are still unresolved.

In a recent review of the literature, Dirschl and Wilson[9] cited several in vitro and general surgical studies (none from orthopaedic clinical trials) that support the use of topical antibiotic irrigation systems. On the basis of these studies, they recommend the use of triple-antibiotic solution for topical irrigation. No recommendation was made regarding use of pulsatile irrigation except that antibiotic irrigation should always be used in conjunction with it, because pulsatile irrigation reduces tissue levels of systemically administered antibiotics.

The use of topical antibiotic irrigation in orthopaedic surgery requires further evaluation, however. Recent studies have shown that some commonly used antibiotic and antiseptic solutions are toxic to local tissue (including osteoblasts) when applied as a topical irrigant.[10,11] The concentrations studied were similar to those currently in use.

A review of the orthopaedic literature disclosed no reference to the absolute volume of irrigant needed to cleanse a contaminated wound, perhaps because there is no universally appropriate amount. The quantity of irrigant needed to cleanse a contaminated wound depends on several factors (e.g., degree of initial injury, amount of contamination, adequacy of exposure, and thoroughness of debridement) and remains a clinical judgment.

The method of delivering the irrigant also remains controversial. Studies performed in the 1970s reported excellent results from the use of pulsatile lavage in highly contaminated soft-tissue wounds.[12-14] However, the use of gravity irrigation systems and bulb-syringe irrigation continues to be popular because of the possible complications of pulsatile irrigation. Additional soft-tissue trauma from the pressure of the pulsatile irrigant may be the final insult to already compromised tissue, and pulsatile irrigation may drive particulate matter deeper into the tissues instead of removing it. The mechanical effects of pulsatile irrigation may also be harmful to nervous and vascular structures that are superficially located in the wound. Despite these potentially negative effects, pulsatile irrigation can deliver a high volume of irrigant over a short period of time and provides additional mechanical debridement.

Antibiotic Therapy

Patients with a severely traumatized extremity will have a compromised host-defense mechanism. In addition, the presence of excessive swelling, devitalized tissue, and ischemia alter the patient's ability to mount an appropriate response to fight infection. For these reasons, prophylactic antibiotics should be given. Several studies have been performed to evaluate their effectiveness in the treatment of the traumatized extremity. Most studies were poorly undertaken, retrospective, and nonrandomized, leaving us without definitive proof that prophylactic antibiotics are really necessary. Nevertheless, most orthopaedic surgeons begin treatment of severe extremity trauma with an antibiotic that covers both Gram-positive and Gram-negative organisms. In a prospective study, Patzakis[15] showed that prophylactic use of a first-generation cephalosporin lowered the rate of infection in the treatment of open fractures. The use of an additional agent to better fight Gram-negative organisms (gentamicin or equivalent) remains controversial, except in the case of the severely contaminated wound. Tetanus prophylaxis and penicillin therapy are appropriate for a wound susceptible to clostridial infection.

The duration of antibiotic prophylaxis also remains controversial. In the past, antibiotics were used for 72 hours. Today, most surgeons will give a short course for 24 to 48 hours. Although there is no definitive study reporting the appropriate duration of therapy, the general trend is toward shorter periods. However, some surgeons rely totally on aggressive surgical debridement followed by copious irrigation and choose not to use antibiotic prophylaxis. Instead, they administer antibiotics only when signs and symptoms of infection appear.

Wound Closure

After thorough debridement and copious irrigation, the wound is assessed for primary closure or temporary coverage. Wounds that are not severe or contaminated, have a viable soft-tissue envelope after debridement, and can be closed without undue tension should undergo primary closure. However, when closing an open wound, the surgeon must be prepared to reexamine the wound under sterile conditions at the first sign of problems; retention of nonviable tissue is not uncommon.

Extensively injured or contaminated wounds should be left open and scheduled for a second-look debridement within 48 to 72 hours. All farm-related injuries and injuries potentially contaminated by *Clostridium* organisms should be left open. These wounds will need a temporary dressing. An intraoperative plastic surgery consultation is advisable for wounds with a large soft-tissue defect. This should be obtained at the initial debridement or the first follow-up debridement. When the wound is clean and viable, temporary coverage is necessary because suboptimal wound oxygen concentrations and desiccation are detrimental to wound healing.

Eight performance characteristics should be considered when choosing a temporary soft-tissue wound dressing[16]: (1) effect on the rate and quality of wound healing, (2) effectiveness as a bacterial barrier, (3) capacity to absorb exudate, (4) occlusivity, (5) biocompatibility, (6) hypoallergenicity, (7) wound contact and release characteristics, and (8) thermal insulation. In addition, patients prefer dressings that are comfortable and convenient, control odor, and reduce pain. One should also take into consideration nursing time and the cost-benefit ratio. With these characteristics in mind, optimal wound dressings can be divided into four categories of fairly new types of dressings: semipermeable films, hydrogels, occlusive hydrocolloids, and synthetic skin substitutes.[16]

Semipermeable films are permeable to water vapor and oxygen but impermeable to liquids and bacteria. Semiocclusive hydrogels are also permeable to water vapor and impermeable to liquids and bacteria. Single-polymer hydrogels form three-dimensional hydrophilic polymers that are more oxygen-permeable than film dressings. Occlusive hydrocolloids have an outer impermeable polyurethane foam and an inner adherent surface. Wound exudate is absorbed by the hydrocolloid matrix, but the hydrocolloids are impermeable to water vapor, oxygen, liquid, and bacteria. Synthetic skin substitutes are usually composed of a two-layer, nontextile, open-matrix polyurethane backed with a microporous polytetrafluoroethylene film. They work much like the occlusive hydrocolloids, but also allow the developing microcirculation to grow into the matrix interstices of the mesh-foam sheet.

The relative disadvantages of these synthetic wound dressings are cost and potential for accumulation of exudate, hematoma, and seroma. The evolution of dressings for the open traumatic wound has progressed from the era of passive absorbent plugs and covers (wet-to-dry gauze dressings) to the era of interactive dressings that establish a controlled microenvironment. The time is not far off when active substances, such as macrophage-derived growth factor and platelet-derived growth factor, will be delivered by temporary dressing covers, thus speeding wound repair.

Temporary wound dressings are left in place until the patient is brought back to the operating room for a second debridement. This is beneficial in many ways. Patients are not subjected to unnecessary procedures; the wound is not exposed to contaminants on the hospital ward; and the tissues are left undisturbed to begin the healing process. Wounds with retained marginal tissue should be dressed, elevated, and scheduled for repeat debridement within 48 to 72 hours. Adjunctive hyperbaric oxygen therapy can be started immediately after debridement of the marginal wound. The dressings are left undisturbed during this form of therapy.[17] At the second debridement, the wound is reexamined, and the viability of the retained marginal tissue is assessed. Definitive closure can be planned at this time.

Definitive Soft-Tissue Coverage

The soft-tissue envelope is composed of several layers of tissues, each with its own specialized function and blood supply. These layers, from superficial to deep, are skin, subcutaneous tissue, fascia, muscle, and periosteum. An open wound is defined as a break in the skin envelope regardless of injury to the remaining soft tissue. One of the primary goals in the management of open wounds is prompt closure, which prevents further death of tissue and infection. Several means of obtaining wound closure are available. All the layers of the soft-tissue envelope will accept a split-thickness skin graft if they are healthy and well vascularized. Although this may not be the best choice of soft-tissue coverage, it meets the first goal in wound management, reconstitution of the epithelial surface of the extremity.

To reconstruct the soft-tissue envelope, the surgeon must define which layers are deficient and the size of the deficiency and then outline a plan for simultaneously treating the bone and soft tissues synergistically. If a wound cannot be closed primarily, the options for definitive closure include delayed primary closure, skin grafting, local-tissue transfer, and free-tissue transfer. Large soft-tissue defects warrant consultation with a plastic surgeon. Godina[18] and others[19] have shown that early coverage of large soft-tissue defects (within 72 hours) is effective and safe and decreases infection rates. These reports have led to changes from the earlier practice of leaving large soft-tissue wounds open to a preference for closed treatment, which encourages granulation. Small wounds over muscle or other well-vascularized tissue can be skin-grafted or left to close secondarily. The major problem with using secondary closure techniques is the increased risk of infection.

Delayed primary closure should be used only if the soft tissues can be reapproximated without undue tension. Relaxing incisions are sometimes needed to facilitate this type of closure. A relaxing incision or multiple small fascial releases ("pie-crusting") are performed only when they allow mobilization of tissue out of the zone of injury. When delayed primary closure is not possible, local- or free-tissue transfer should be performed.

Skin grafting, although a free-tissue transfer, is simple and can be performed by orthopaedic surgeons. The choice of one of the several available types of skin grafting depends on the characteristics of the defect. Split-thickness skin grafts have a higher rate of success, or "take," than full-thickness grafts but do not provide as much padding. Split-thickness grafts contract more than full-thickness grafts, but both will ultimately contract with time. Both grafts are insensate, and care should be taken to avoid their placement in areas subject to pressure. Wounds that are too complex to accept a skin graft (i.e., exposed bone, a joint, or a vital structure) require the addition of well-vascularized tissue (either a local or a distant flap) to achieve wound closure.

Soft-tissue flaps have been classified in several ways to allow better communication, incorporate safety in design, and provide a basis for the development of new flaps.[20] These classifications are based on the composition and blood supply of the flap and the method of transfer. For the sake of simplicity, we will classify flaps on the basis of the method of transfer.

Local-tissue flaps are an attractive means of covering soft-tissue defects. Numerous local flaps are available for transfer, and the type of flap transferred depends on several factors, including the location of the soft-tissue defect, the nature of the injury, and the availability of local tissues.[20,21] Emphasis has recently been placed on vascular territories (angiosomes or venosomes) that can be used as local rotational or island flaps. Local rotational flaps, consisting of muscle, skin, fascia, or some combination thereof, add much-needed vascularized tissue, obliterate dead space, and help close the wound without tension.

Unfortunately, local tissues are often unavailable for transfer because of the initial traumatic event. If zone-of-injury tissues are used for transfer, subsequent breakdown and loss of graft can occur. The treating physicians should be aware of this and should monitor the flap closely. When local tissues cannot be used because of initial injury, wound location, or donor-site deficiencies, free flaps must be considered.

The purposes of free-tissue transfers are much the same as those of local-tissue transfers—to fill a dead space, to add vascularized tissue, and to close a wound. A crucial difference is that the use of a free flap requires technical expertise in the field of microvascular surgery. Two criteria must be met before free-tissue transfer is performed. The soft-tissue wound must be clean and viable, and the donor tissue must be available, expendable, and least morbid.

An alternative to free-tissue transfer is the use of functional composite free flaps, such as innervated myocutaneous flaps. Functional composite free flaps represent state-of-the-art reconstruction in which several functions are achieved in one procedure (i.e., soft-tissue coverage, bone restoration, and muscle function).

Soft-tissue defects that are associated with bone defects are treated with tissue transfer followed by early bone grafting. Some surgeons place space-occupying material in the bone defect.[22] This material can be cement, silicone, or a biodegradable spacer. When a spacer is used to fill a dead space, antibiotics should be administered.[23] The reader is referred to the references for further information regarding the techniques used for placement of antibiotic cement spacers.[22,23] Few surgeons place autologous bone graft at the time of coverage. However, there is basic-science support for this concept, assuming the wound is clean and completely viable.

Bone Stabilization

After adequate treatment of the soft-tissue injury, severely traumatized extremities with one or more associated fractures must be stabilized. High-energy extremity injuries typically exhibit unstable fracture patterns requiring surgical stabilization of associated fractures and soft tissues.[24] The choice of a fixation device depends on several factors, including the type and location of the fracture, the severity of soft-tissue damage, and subsequent soft-tissue coverage requirements.[24]

Open reduction and internal fixation, intramedullary nailing, and external fixation are the three most accepted means of surgical skeletal fixation. Open reduction and internal fixation is the most invasive of these techniques. Because soft-tissue injuries due to high-energy trauma will seldom tolerate extensive dissection, plate fixation is generally inappropriate. However, if the surgeon considers the soft-tissue envelope to be viable and the fracture to be adequately exposed, plating the fracture is an acceptable means of fixation. Gotzen reported three criteria for successful plating of an open fracture: (1) the plate will lie under viable soft tissue, (2) no further soft-tissue stripping will be necessary for plating, and (3) the plating will produce a stable construct.[25] The fractures that are best treated with plate fixation are juxta-articular and metaphyseal fractures with diaphyseal extension.

Intramedullary nailing has evolved over the past several years and is today the most commonly used form of skeletal stabilization for diaphyseal long-bone fractures. Several authors have reported excellent clinical results and few complications with the use of intramedullary nailing techniques.[1,26] Despite this, several issues regarding the use of intramedullary nails remain controversial, such as exchange nailing and unreamed nailing. Clinical trials are currently under way to try to resolve these issues.

External fixation, the least invasive form of surgical skeletal fixation, is a widely accepted form of treatment for the severely traumatized extremity. A severely injured soft-tissue envelope will not tolerate an acute extensive surgical dissection. Placement of an external fixator stabilizes the skeleton and provides excellent soft-tissue access. External fixator frames can be unilateral, circular, or hybrid. Circular and hybrid frames incorporate thin wires into the frame. Thin wire frames are generally used for juxta-articular fractures or fractures with segmental bone loss that may require distraction osteogenesis. Regardless of the frame used, all can be disassembled for each debridement, allowing the soft tissues to be completely reevaluated. If intramedullary nailing is performed early, the reduced fracture will occasionally limit exposure of the deeper tissues at the time of the second debridement. Although delayed primary nailing after external fixation is a controversial topic, Blachut et al[26] have reported it to be safe when performed within 2 weeks of injury.

The goal of skeletal stabilization is to stabilize the soft tissues and obtain union. The method of fixation chosen should facilitate this process. Although temporary skeletal fixation can be used, the method of initial fixation should be adequate for definitive fixation if necessary. Staged skeletal fixation (i.e., external fixation with delayed primary nailing and conversion of external fixation to open reduction and internal fixation) should be reserved for the most complex injuries and difficult fracture patterns.[26] After skeletal stabilization, definitive soft-tissue coverage is essential. Fractures that may be slow to unite, such as those with segmental bone defects or axially unstable fracture patterns, should be scheduled for autologous bone grafting as soon as the wound has stable coverage and is free of drainage.

Rehabilitation

After initial assessment, management, and definitive closure of extremity wounds, associated injuries should be treated aggressively. Surgical intervention is often indicated, as severely traumatized extremities adversely affect patient mobilization, especially if a lower extremity is injured. After soft-tissue wounds have been treated and skeletal injuries have been stabilized, early mobilization of the joints above and below the injury is desirable whenever possible. Physical therapy should be instituted as appropriate, including the judicious use of various rehabilitative modalities, such as electric stimulation, continuous passive motion machines, and range-of-motion exercises. Controlled studies to determine which modalities are both clinically effective and cost-effective are needed to guide the appropriate use of physical therapy.

Summary

The management of high-energy extremity fractures continues to evolve. It is clear that appropriate management of the soft-tissue envelope is essential to a good outcome. Although there are several areas of soft-tissue management that require further study, advances have been made in fighting infection and salvaging functional extremities. To ensure appropriate decision making and accurate prediction of outcome, orthopaedic surgeons who treat high-energy extremity trauma must adhere to strict principles of soft-tissue management.

Acknowledgment: The authors are grateful to Paula I. Robbins, PhD, for assistance in manuscript preparation.

References

1. Brumback RJ: Open tibial fractures: Current orthopaedic management. *Instr Course Lect* 1992;41:101-117.
2. Gustilo RB, Anderson JT: Prevention of infection in the treatment of one thousand and twenty-five open fractures of long bones: Retrospective and prospective analyses. *J Bone Joint Surg Am* 1976;58:453-458.
3. Gustilo RB, Mendoza RM, Williams DN: Problems in the management of type III (severe) open fractures: A new classification of type III open fractures. *J Trauma* 1984;24:742-746.
4. Brumback RJ, Jones AL: Interobserver agreement in the classification of open fractures of the tibia: The results of a survey of two hundred and forty-five orthopaedic surgeons. *J Bone Joint Surg Am* 1994;76:1162-1166.
5. Tscherne H, Sudkap NP: Pathophysiology of open fractures and principles of their treatment: Review [in Czech]. *Acta Chir Orthop Traumatol Cech* 1990; 57:193-212.
6. Bonanni F, Rhodes M, Lucke JF: The futility of predictive scoring of mangled lower extremities. *J Trauma* 1993;34:99-104.
7. Roessler MS, Wisner DH, Holcroft JW: The mangled extremity: When to amputate? *Arch Surg* 1991;126:1243-1249.
8. Dirschl DR, Dahners LE: The mangled extremity: When should it be amputated? *J Am Acad Orthop Surg* 1996;4:182-190.
9. Dirschl DR, Wilson FC: Topical antibiotic irrigation in the prophylaxis of operative wound infections in orthopedic surgery. *Orthop Clin North Am* 1991;22:419-426.
10. Cooper ML, Boyce ST, Hansbrough

JF, et al: Cytotoxicity to cultured human keratinocytes of topical antimicrobial agents. *J Surg Res* 1990;48:190-195.
11. Kaysinger KK, Nicholson NC, Ramp WK, et al: Toxic effects of wound irrigation solutions on cultured tibiae and osteoblasts. *J Orthop Trauma* 1995;9: 303-311.
12. Gross A, Cutright DE, Bhaskar SN: Effectiveness of pulsating water jet lavage in treatment of contaminated crushed wounds. *Am J Surg* 1972; 124:373-377.
13. Brown LL, Shelton HT, Bornside GH, et al: Evaluation of wound irrigation by pulsatile jet and conventional methods. *Ann Surg* 1978;187:170-173.
14. Rodeheaver GT, Pettry D, Thacker JG, et al: Wound cleansing by high pressure irrigation. *Surg Gynecol Obstet* 1975;141:357-362.
15. Patzakis MJ: Management of open fracture wounds. *Instr Course Lect* 1987;36:367-369.
16. Esterhai JL Jr: Management of soft-tissue wounds associated with open fractures. *Instr Course Lect* 1990;39:483-486.
17. Uhl E, Sirsjö A, Haapaniemi T, et al: Hyperbaric oxygen improves wound healing in normal and ischemic skin tissue. *Plast Reconstr Surg* 1994;93:835-841.
18. Godina M: Early microsurgical reconstruction of complex trauma of the extremities. *Plast Reconstr Surg* 1986; 78:285-292.
19. Cierny G III, Byrd HS, Jones RE: Primary *versus* delayed soft tissue coverage for severe open tibial fractures: A comparison of results. *Clin Orthop* 1983;178:54-63.
20. Ciresi KF, Mathes SJ: The classification of flaps. *Orthop Clin North Am* 1993;24:383-391.
21. Galumbeck M, Colen LB: Coverage of lower leg: Rotational flap. *Orthop Clin North Am* 1993;24:473-480.
22. Levin LS: The reconstructive ladder: An orthoplastic approach. *Orthop Clin North Am* 1993;24:393-409.
23. Ostermann PAW, Henry SL, Seligson D: The role of local antibiotic therapy in the management of compound fractures. *Clin Orthop* 1993:295:102-111.
24. Burgess AR, Poka A, Brumback RJ, et al: Management of open grade III tibial fractures. *Orthop Clin North Am* 1987;18:85-93.
25. Tscherne H, Gotzen L: *Fractures With Soft Tissue Injuries.* Berlin: Springer-Verlag, 1984, pp 152-158.
26. Blachut PA, Meek RN, O'Brien PJ: External fixation and delayed intramedullary nailing of open fractures of the tibial shaft: A sequential protocol. *J Bone Joint Surg Am* 1990; 72:729-735.