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The Use of Ilizarov External Fixation Following Failed Internal Fixation

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Summary: Failure of internal fixation following treatment of a fracture or fracture nonunion presents a challenging clinical situation. In certain cases, Ilizarov external fixation may be the preferred method to treat bony injuries that have failed to unite following one or more attempts at internal fixation. This paper reviews the modes of failure following internal fixation, revision internal fixation as an option, and the application of the Ilizarov method following failure of internal fixation. **Key Words:** Ilizarov—Nonunion—Delayed union—Revision surgery.

Failure of fracture or fracture nonunion treatment following internal fixation can be defined in many ways. The failure can be related to the mechanical construct or to the local biology at the site of injury, or both.

Mechanical instability following internal fixation results in excessive motion at the site of bony injury impairing the fracture repair process. This instability often results from, and can further potentiate, hardware loosening and fatigue failure, which in turn lead to still further instability. Biologic failure can result from inadequate vascularity or poor bone-to-bone contact, or both.

A wide variety of options are currently available for the treatment of a fracture or fracture nonunion that has failed internal fixation. In many instances, a revision surgery using a similar or a different type of internal fixation will lead to a successful outcome. In certain cases that have failed internal fixation, however, the Ilizarov method may offer significant advantages. Examples of such cases include those: 1) that have failed to unite despite multiple well-executed attempts using internal fixation; 2) with bony fragments that are too small or too numerous for revision surgery with internal fixation, as is often seen with periarticular injuries; 3) with an associated infection of bone; 4) with an associated bony defect; 5) with osteopenic states where bony purchase can be problematic with internal fixation, particularly screw fixation; and 6) with severe irreducible deformity at the site of a stiff (hypertrophic) nonunion.

A variety of treatment modes using the Ilizarov method have been described. These include monofocal, bifocal, and trifocal techniques. An Ilizarov method treatment mode can be chosen that addresses the specific problems presented for a particular case of failed internal fixation. This paper reviews the modes of failure following internal fixation, the use of revision internal fixation as a treatment option, and the application of the Ilizarov method following failure of internal fixation.

MODES OF FAILURE FOLLOWING INTERNAL FIXATION

The most basic requirements for fracture or fracture nonunion healing are: 1) mechanical stability, 2) an adequate blood supply, and 3) bone-to-bone contact. The absence of one or more of these factors predisposes to problems with bone healing following internal fixation.[5]

The basic requirements for healing may be negatively affected by: 1) the severity of the injury, 2) suboptimal surgical fixation from either a poor treatment plan or a good treatment plan carried out poorly, or 3) a combination of the injury severity and the suboptimal technical performance of the operative procedure.

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Mechanical Instability

Mechanical instability can follow internal fixation and results in excessive motion at the fracture site. Factors producing mechanical instability include: 1) inadequate fixation with hardware; 2) distraction at the fracture site with a gap between the fracture surfaces; 3) bone loss; and 4) poor bone quality for purchase. In the presence of an adequate blood supply, excessive motion at the site of bony injury results in abundant callus formation, widening of the fracture line, failure of fibrocartilage mineralization, and, ultimately, a nonunion that will inevitably result in hardware failure.

Inadequate fixation following plate and screw stabilization results from implants that are too small in size or too few in number, or from poor technical performance of the procedure. In general, small fragment screws (3.5 mm) are more likely to loosen or fatigue than large fragment screws (4.5 mm). Shorter plates are not as effective at resisting cantilever loads as longer plates, which benefit from both an increased moment arm and the ability to place a greater number of screws.

Intramedullary nails function as internal splints with contact between the implant and bone along the medullary canal. These devices benefit from their load-sharing characteristics. In general, the ultimate strength of an intramedullary nail is greater than that of plates and screws. Therefore, early fatigue failure of a nail is less common than with plate and screw fixation. However, the rigidity afforded by an intramedullary nail is considerably less than that of plate and screw fixation. Although a nail is less likely to fatigue than plates and screws, the fixation they provide permits more motion at the site of bony injury, which may contribute to problems with bone healing.

Inadequate Vascularity

Loss of blood supply to the surfaces at a bony injury may arise because of the severity of the injury or because of surgical dissection. Open injuries and high-energy closed injuries are associated with soft tissue stripping and damage to the periosteal blood supply. These injuries can also disrupt the nutrient vessels and thus impair the endosteal blood supply. A number of studies have shown a relationship between the extent of soft tissue injury and the rate of the fracture nonunion.[6,8,10] Whatever the cause, inadequate vascularity results in necrotic bone at the site of injury that inhibits the normal biology of bony healing.

Poor Bone Contact

Bone-to-bone contact is an important requirement for bony repair following internal fixation. Poor bone-to-bone contact at the site of bony injury may result from: 1) soft tissue interposition, 2) malposition or malalignment of the fracture fragments, 3) bone loss, and 4) distraction of the fracture fragments. Whatever the etiology, poor bone-to-bone contact compromises mechanical stability and creates a defect that the repair process must bridge. As these defects increase in size, the probability of bony union following internal fixation decreases. In addition, the likelihood of hardware failure increases.

REVISION INTERNAL FIXATION AS AN OPTION

Two primary treatment options exist following failure of internal fixation: 1) revision internal fixation, and 2) the Ilizarov method.

Revision Internal Fixation

In many cases, revision internal fixation following one or more prior failed internal fixations may lead to a successful clinical outcome. The revision surgery may use plate and screw fixation, or intramedullary nail fixation, or, in rare instances, both.

Revision Plate and Screw Fixation

The principles of revision surgery using plate and screw fixation include: 1) stable internal fixation under compression; 2) decortication; 3) bone grafting in nonunions associated with gaps or poor vascularity; 4) leaving the nonunion tissue undisturbed in cases of hypertrophic nonunions; and 5) early return to function. The mechanical properties of the revision plate stabilization may be maximized using a variety of techniques, including the use of: 1) longer plates; 2) thicker plates; 3) fixed angle devices; 4) dual plating; 5) interfragmentary screws; 6) larger diameter screws; 7) a greater number of screws; and 8) screw augmentation techniques (such as the use of screws with locking nuts, or with polymethylmethacrylate).

Revision Intramedullary Nail Fixation

Revision surgery using an intramedullary nail following failed internal fixation can be classified as either: 1) intramedullary nail fixation, or 2) exchange nailing.

Intramedullary nailing is an excellent method of providing mechanical stability to a bony injury that has failed prior internal fixation. The method is useful for nonunions of the long bones whose injuries have previously been treated by a method other than an intramedullary nail, such as following failed plate and screw fixation. Intramedullary nail fixation is particularly useful for lower extremity nonunions because of the ultimate strength and load-sharing characteristics of intramedullary nails. In addition, intramedullary implants are an excellent treatment option for patients with osteopenic states where bone purchase may be poor.

Intramedullary nail fixation as a treatment for nonunion is commonly combined with a biologic method such as open grafting, intramedullary grafting, or intramedullary reaming. These techniques are used to stimulate the local biologic activity at the nonunion site, but the intramedullary nail itself is strictly a mechanical treatment method.

Intramedullary nail fixation as a treatment for nonunion following failed plate and screw fixation is most commonly used in the tibia. Here, healing rates for nonunions have been reported to exceed 90%.[21,32,34]

Exchange Nailing Following Failed Intramedullary Nail Fixation

In the previous section, intramedullary nail fixation following failure of plate and screw fixation was discussed. That method is distinguished from exchange nailing in that the latter is a method that produces both mechanical and biologic effects. By definition, exchange nailing requires the removal of a previously placed intramedullary nail and the placement of a new larger diameter nail.

Exchange nailing stimulates healing of nonunions by improving the local mechanical environment in two ways, and by improving the local biologic environment in two ways. Enlargement of the medullary canal via reaming allows for the placement of a larger diameter nail that is stronger and stiffer (provided that the manufacturer does not decrease the wall thickness as the nail diameter increases). The stiffer, stronger nail augments mechanical stability at the nonunion site, which promotes bony union. The second mechanical benefit of reaming is the widening and lengthening of the isthmic portion of the medullary canal. This enhances mechanical stability by increasing the endosteal cortical contact area of the nail. This effect is particularly dramatic when exchange nailing is performed on a long bone that was initially treated with a small diameter nail using an unreamed technique.

Biologically, the products of reaming act as local bone graft at the nonunion site and thus stimulate medullary healing. The second biologic benefit of reaming is related to the resulting changes in the endosteal and periosteal circulation. Medullary reaming results in a substantial decrease in endosteal blood flow.[4,18] This loss of endosteal blood flow following reaming is accompanied by a dramatic increase in both periosteal flow[28] and periosteal new bone formation.[11]

Exchange nailing is an excellent treatment method when good bone-to-bone contact is present at the nonunion site. The technique is less well suited for cases with large partial or complete segmental bone defects.

In nonunions of the tibia, exchange nailing achieves healing in 90% to 95% of cases.[10,33,38] In the femoral shaft, exchange nailing remains the treatment of choice for nonunions, but the rate of success is probably lower than that seen for the tibia.[9,14,23,37] In the supracondylar femoral region, exchange nailing often produces poor results and other treatment methods should be used.[19] In the humeral shaft, poor results have been reported for exchange nailing for nonunions.[20]

THE ILIZAROV METHOD FOLLOWING FAILED INTERNAL FIXATION

For certain fractures and fracture nonunions that have failed internal fixation, the Ilizarov method offers many advantages. Some of these advantages are that the Ilizarov method: 1) is primarily percutaneous, minimally invasive, and typically requires only minimal soft tissue dissection; 2) can promote generation of bony tissue; 3) is versatile; 4) can be used in the presence of acute or chronic infection; 5) allows for stabilization of small intraarticular or periarticular bone fragments; 6) allows for simultaneous bony healing and deformity correction; and 7) allows for immediate weightbearing and early joint mobilization.

The Ilizarov construct provides mechanical strength and stability, with resistance to shear and rotational forces. The Ilizarov method is somewhat unique in that the 1.8 mm tensioned wires produce a "trampoline effect" during weightbearing activities, which promotes osseous integration by mechanically stimulating the site of bony injury. Treatment with the Ilizarov method can be augmented through frame modification when a fracture or fracture nonunion fails to show progression to healing. Generally, frame modification is not painful, does not require anesthesia, and can be performed in the office. Frame modification should not be considered failure of the Ilizarov method; rather, it is considered continued treatment. By contrast, modifying plate and screw fixation or intramedullary nail fixation requires repeat surgical intervention.

A variety of modes of treatment can be employed using the Ilizarov method. These include compression, distraction, lengthening, and bone transport. Treatment

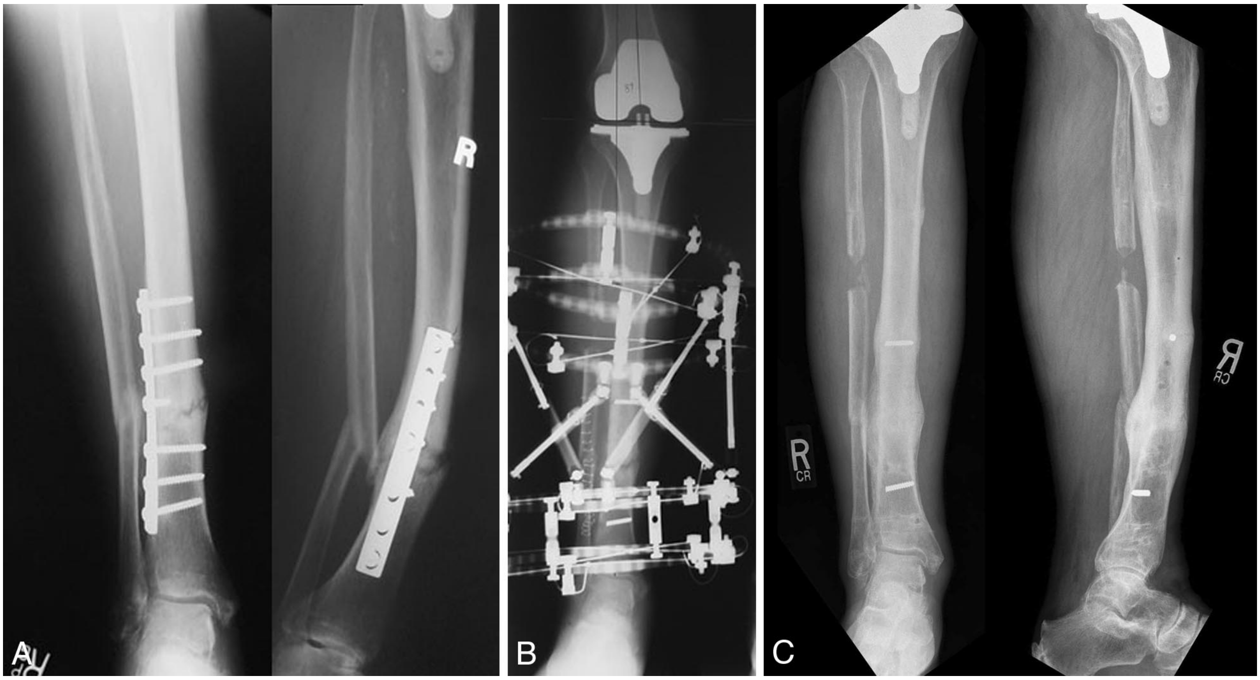

FIG. 1. Failure of plate and screw fixation. **(A)** Anteroposterior and lateral radiographs of a 70-year-old man referred in with a distal tibial third nonunion below a total knee arthroplasty. The patient had a past medical history of multiple medical problems, including diabetes mellitus. The patient had had three prior failed attempts at internal fixation and bone grafting. In this case, the failure of internal fixation treatment should be thought of as biologic failure as the bone failed to unite but the hardware had remained intact for several months at the time of presentation. **(B)** Anteroposterior radiograph during Ilizarov treatment of the nonunion with concomitant deformity correction. Because this patient required removal of the plate and screw fixation, the patient was treated with local bone grafting at the time of hardware removal. To facilitate deformity correction, the patient was also treated with partial excision of the fibula. **(C)** Anteroposterior and lateral radiograph of the tibia following removal of the Ilizarov external fixator. Note the solid bony union at the nonunion site with correction of the patient's deformity.

may be monofocal, such as with simple compression or distraction across the site of bony injury. Bifocal treatment denotes that two healing sites exist, such as in the case of a bone transport where healing must occur at both the distraction site (regenerate bone formation) and the docking site (via compression). Trifocal treatment denotes that three healing sites exist, such as in a double-level bone transport.

Many cases of fracture or fracture nonunion that have failed internal fixation respond well to treatment with the Ilizarov method. Examples of such cases include: 1) those that have failed to unite despite multiple well-executed attempts using internal fixation; 2) those with bony fragments that are too small or too numerous for revision surgery with internal fixation, as is often seen with periarticular injuries; 3) those with an associated infection of bone; 4) those with an associated bony defect; 5) those with osteopenic states where bony purchase can be problematic with internal fixation, particularly screw fixation; and 6) those with severe irreducible deformity at the site of a stiff (hypertrophic) nonunion.

Failure to Unite Despite Multiple Well-Executed Attempts Using Internal Fixation

The Ilizarov method may be successfully applied for treatment of fracture or fracture nonunion after failure of multiple attempts using plates and screws or multiple failed exchange nailings. Failure of well-executed internal fixation may be associated with necrotic avascular bone segments that fail to unite despite achieving excellent mechanical stability.

Failure of Plate and Screw Fixation

Failure of plate and screw fixation may arise as a result of failure of primary bone healing and may ultimately display bone resorption with widening at the fracture site (Figs. 1 and 2). In cases displaying bone resorption, hardware removal and gradual compression over the course of several weeks using the Ilizarov method is often successful in promoting bony union. In all instances (other than cases with a hypertrophic nonunion or those with gross purulent drainage), the adjacent bony surfaces should be prepared using a decortication technique and the bony bed should be

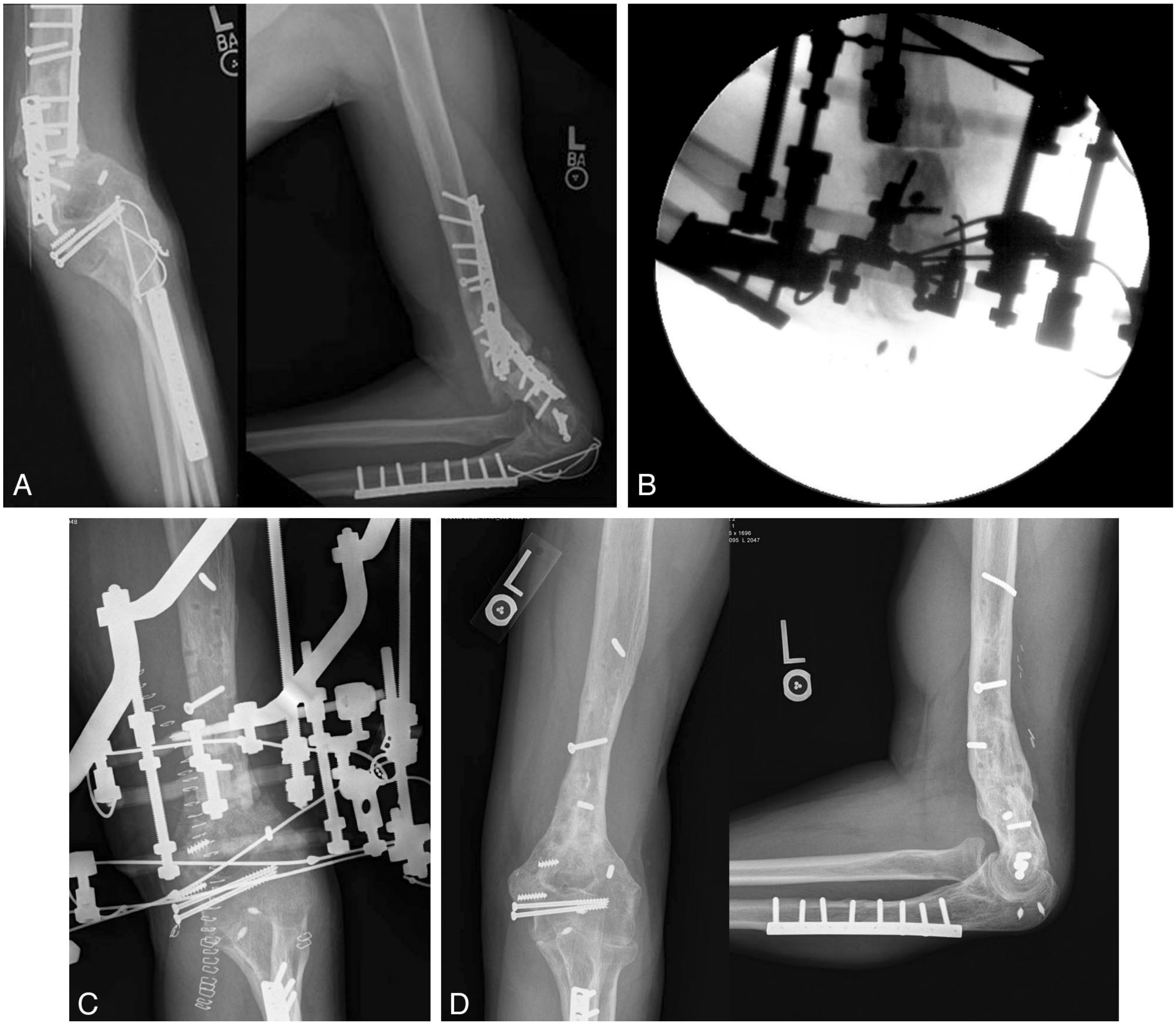

FIG. 2. Failure of plate and screw fixation. **(A)** Presenting radiographs of a 34-year-old man following failed internal fixation for a severe distal humeral nonunion. This patient had failed four prior attempts at an outside facility using conventional internal fixation and bone grafting techniques. **(B)** Intraoperative radiograph following bony resection shows good bony contact with early compression using the Ilizarov external fixator. **(C)** Anteroposterior radiograph of the patient during treatment with the Ilizarov method showing the multiple points of fixation using the tensioned thin wire technique of the Ilizarov method. **(D)** Final anteroposterior and lateral radiographs showing solid bony union. The patient has regained a 110° arc of motion and has excellent function.

grafted with autogenous cancellous bone graft at the time of plate and screw removal.

Slow, gradual compression is generally applied at a rate of 0.25 to 0.5 mm per day for a period of 2 to 4 weeks. Once the bone ends are in contact, the rings spanning the site of bony injury are moving closer together to a greater extent than are the bone fragments. When this occurs, the wires on either side of the fracture or fracture nonunion site bow. Compression stimulates bony healing for most fracture or fracture nonunions following failed internal fixation. In the optimal scenario, the bone fragments have large, transversely oriented adjacent surfaces, which allow good bony contact and are stable to axial compression. Simple monofocal compression is usually unsuccessful for fractures or fracture nonunions associated with infection with purulent drainage and large intervening segments of necrotic bone.

Failure of Exchange Nailing

Failed exchange nailing is an uncommon, but challenging, problem (Fig. 3). Failure of exchange nailing may be related to either a biologic problem or micromo-

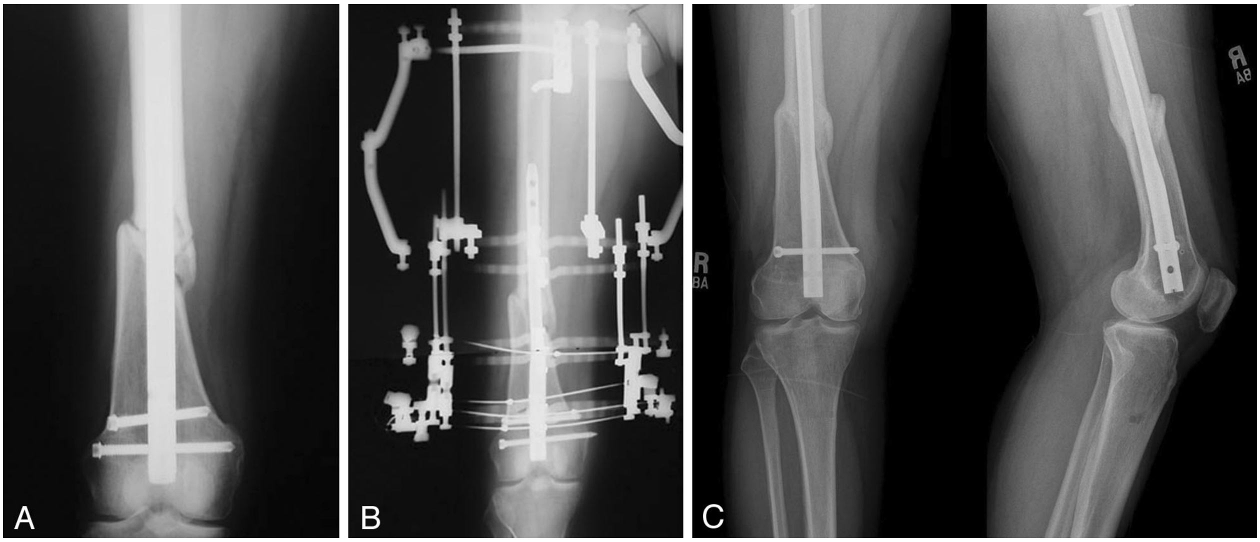

FIG. 3. Failure of exchange nailing. **(A)** Anteroposterior radiograph of a 39-year-old woman with a history of a fracture treated with a retrograde nail. Despite the somewhat benign appearance of the fracture, this patient was referred in having failed two prior attempts at exchange nailing. The patient presented with severe thigh and knee pain rated as 9 out of 10. **(B)** Anteroposterior radiograph following placement of an Ilizarov external fixator over a smaller diameter retrograde intramedullary nail dynamically locked with screw fixation only distally. Note the bending of the distal Ilizarov wires indicating good compression at the nonunion site using the SCONE (slow compression over a nail using external fixation) technique. Also note the improved bony contact at the nonunion site. **(C)** Final anteroposterior and lateral radiograph showing solid bony union following static locking of the nail and removal of the Ilizarov external fixator. The patient has resumed full preinjury activity and rates her pain at 0 out of 10.

tion around the nail, or both. Slow compression over a nail using external fixation (SCONE) is a useful method for certain patients who have failed treatment using exchange nail techniques.[5] The surgical procedure for the SCONE technique involves removing the retained intramedullary nail and inserting a smaller diameter nail (typically 2 to 3 mm smaller) that is dynamically locked. No reaming of the medullary canal is performed. The smaller diameter nail allows the bone fragments to slide over the nail without interference during the compression phase of treatment. Next, an Ilizarov external fixator that has been constructed to allow the patient to slowly compress across the nonunion, during the course of each day, is applied. Progression of bony contact and bony union can be monitored using plain radiographs and CT scans. Following bony union, the intramedullary nail is statically locked and the Ilizarov external fixator is removed.

The SCONE method augments stability and allows for monofocal compression at the nonunion site. The presence of the nail in the medullary canal encourages pure compressive forces and discourages translational and shear moments.

Bony Fragments Too Small or Numerous for Revision Surgery With Internal Fixation

Periarticular fractures or fracture nonunions that have failed treatment with internal fixation often present with small bony fragments that are not readily amenable to revision internal fixation (Fig. 4). The 1.8 mm tensioned wires used in the Ilizarov method allow small bony fragments to be captured and reduced, thus providing bone-to-bone contact and stimulating bony healing. The mechanical stability afforded by the Ilizarov construct further enhances the environment in which bony healing of the fragments occurs.

The use of the Ilizarov method to treat a periarticular fracture or nonunion that has small bony fragments following failed internal fixation may require spanning an adjacent joint with the Ilizarov external fixator to achieve adequate stability. Once radiographic evidence of progression to bony healing is seen, the Ilizarov external fixator can be modified so that it no longer spans the adjacent joint. This allows the patient to perform range of motion exercises to prevent contractures and to maintain muscle function.

Stiffness or deformity of the joints adjacent to the site of fracture or fracture nonunion following failed internal fixation can limit outcome if they are not identified and addressed. For example, realignment of a stiff nonunion that has produced a compensatory joint deformity without treating the deformity results in a straight long bone, but a disabled limb. A detailed discussion of this topic is beyond the scope of this paper, but has been well described elsewhere.[5]

FIG. 4. Bony fragments too small for revision surgery with internal fixation. **(A)** Anteroposterior radiograph of a patient with a grossly infected distal tibial nonunion. **(B)** Clinical photograph. **(C)** Intraoperative radiograph of the distal tibia and ankle following segmental bony resection of infected and necrotic bone. **(D)** Early postoperative anteroposterior and lateral radiographs following application of the Ilizarov external fixator. Note how the tensioned wires capture the very small distal fragment. **(E)** Sequence of radiographs showing progression of the bony regenerate site during bone transport. (*Figure continues*)

FIG. 4. (*Continued*) (F) Anteroposterior radiograph of the regenerate at the completion of bone transport (not shown on this radiograph is docking at the distal site). Note the progressive maturation of the long column of bony regenerate. **(G)** Final radiographs show solid bony union of the entire length of the tibia. **(H)** Clinical photographs showing full weightbearing and excellent range of knee and ankle motion.

Associated Infection of Bone

An infection of a fracture or fracture nonunion following failed internal fixation poses a dual challenge that is characterized by two of the most difficult orthopaedic entities to treat: bone infection and ununited fracture. An infection of a fracture or fracture nonunion following failed internal fixation is often accompanied by incapacitating pain (often with narcotic dependency), soft tissue problems, deformities, joint problems (contractures, deformities, limited range of motion), motor and sensory dysfunction, osteopenia, poor general health, depression, and a myriad of other problems.

The goals in treating an infection of a fracture or fracture nonunion following failed internal fixation are: 1) to obtain solid bony union; 2) to eradicate the infection; and 3) to maximize function of the extremity and the patient. Before embarking on a course of treatment, the length of time required, the number of operative procedures anticipated, and the intensity of the treatment plan must be discussed with the patient and family. The course of treatment is difficult to predict and the possibility of persistent infection and nonunion despite appropriate treatment should be discussed, and the possibility of future amputation should be considered.

The treatment strategy for bone infection following failed internal fixation is dependent on the nature of the infection; specifically, whether the infection is draining, nondraining-active, or nondraining-quiescent.[29] Treatment

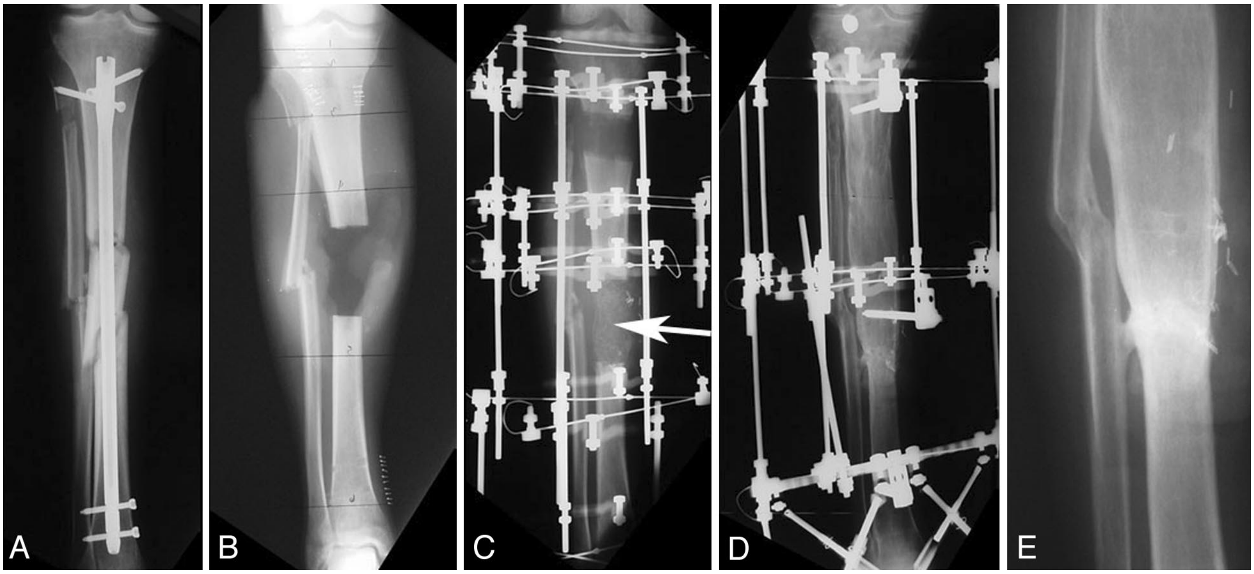

FIG. 5. Associated infection of bone/active draining infection. **(A)** Anteroposterior radiograph of a severe open tibia fracture referred in 3 months following intramedullary nail fixation at an outside facility. The patient presented with abundant gross purulence draining from a large open wound with exposed bone and hardware. **(B)** Anteroposterior radiograph following bony resection and removal of the intramedullary nail. **(C)** Anteroposterior radiograph during bone transport using the Ilizarov method. Note the early regenerate at the proximal corticotomy site. Also note that the docking site cavity had been grafted with copious cancellous autograft bone (arrow) at the time of final soft tissue coverage using a free flap. **(D)** Anteroposterior radiograph in the Ilizarov external fixator following successful bone transport. Note the maturation of the regenerate and solid healing at the docking site without the need for further operative bone grafting procedures. **(E)** Final anteroposterior radiograph following Ilizarov removal shows solid healing at the docking site.

involves both a biologic and a mechanical approach, both of which are addressed with the Ilizarov method.

Active Draining Infections

When purulent drainage is ongoing, the injury site will take longer and be more difficult to heal. An actively draining infection following failed internal fixation necessitates serial radical debridements to eliminate the infection (Fig. 5). The first debridement should include removal of all orthopaedic hardware in the zone of the infection. In addition, deep cultures should be obtained, including specimens of soft tissues and bone. Perioperative antibiotics should be stopped for at least 1 week prior to obtaining deep intraoperative cultures. Excision of all necrotic soft tissues (e.g., fascia, muscle, abscess cavities, and sinus tracts), bone, and foreign bodies, should be performed. The soft tissue sinus tract should be sent for pathologic specimen to rule out carcinoma.

Following debridement of an actively draining bone infection, a dead space is commonly present. The initial treatment typically involves insertion of antibiotic-impregnated polymethylmethacrylate beads, and a bead exchange is performed at the time of each serial debridement. The dead space can subsequently be managed in a number of ways. Currently, the most widely used method involves filling the soft tissue dead space with a rotational vascularized muscle pedicle flap (e.g., gastrocnemius or soleus[27]) or a microvascularized free flap (e.g., latissimus dorsi, rectus, others).[35,36] Another method of managing the dead space involves open wound care with moist dressings, as in the Papineau technique,[26] until granulation occurs and skin grafting can be performed.

Generally, a consulting infectious disease specialist directs systemic antibiotic therapy. Following procurement of deep surgical cultures, the patient is placed on broad-spectrum intravenous antibiotics as the culture results are pending. Antibiotic coverage is later directed at the infecting organisms when the culture results are available.

After elimination of infection, the resulting bony defects can be reconstructed using a variety of techniques available with the Ilizarov method, as will be discussed in the section that follows on Associated Bony Defects.

Active Nondraining Infections

Nondraining but active bone infections following failed internal fixation present with swelling, tenderness, and local erythema (Fig. 6). The history often includes episodes of fever or other constitutional symptoms. These bone conditions are treated using similar principles to those described for actively draining bone infections: debridement, intraoperative cultures, soft tissue

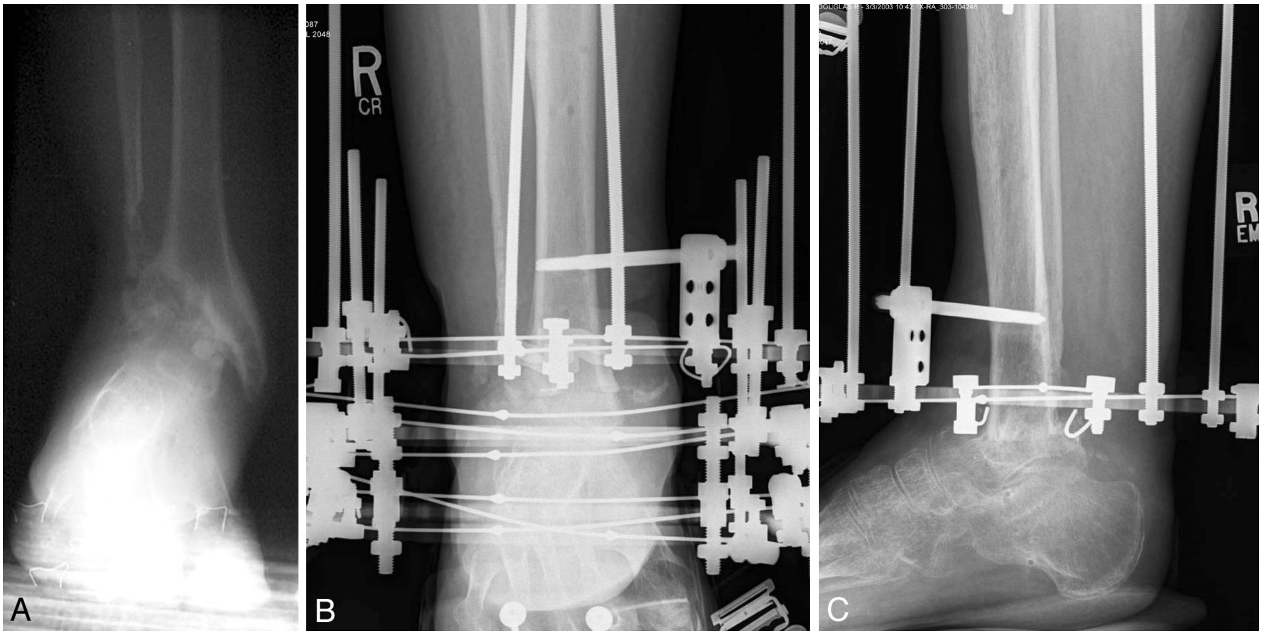

FIG. 6. Associated infection of bone/active nondraining infections. **(A)** A presenting radiograph of a 48-year-old man referred in following multiple failed attempts at an ankle fusion using a variety of internal fixation techniques. The patient is HIV-positive and has had a history of recurrent episodes of fever and cellulitis to the ankle region, including several recent episodes. **(B)** The patient was treated with debridement and bony resection, acute shortening, and compression at the junction of the tibia and talus. This anteroposterior radiograph was taken during slow continued gradual compression following acute compression in the Ilizarov external fixator. **(C)** This lateral radiograph following removal of all foot fixation shows solid fusion of the ankle. The Ilizarov external fixator remains in place as the patient is now undergoing limb lengthening through a proximal tibial corticotomy.

management, mechanical stabilization, bone healing stimulation, and systemic antibiotic therapy. These cases typically require hardware removal, incision and drainage of an abscess, and excision of only small amounts of bone and soft tissues. Nondraining bone infections are frequently managed with primary closure following incision and drainage or may be managed with a closed suction-irrigation drainage system until the infection becomes quiescent.

Nondraining Quiescent Infections

Nondraining quiescent infections following failed internal fixation are those in patients with a history of infection but without drainage or symptoms for 3 or more months[29] or without a history of infection but with positive nuclear medicine studies (Fig. 7). In these cases, the Ilizarov method may be used to promote bony healing by applying compression across the fracture site without requiring open debridement or bone grafting.[31]

Associated Bony Defects

Segmental bone defects associated with fractures or fracture nonunions result from: 1) high energy open fractures; 2) surgical debridement of devitalized bone fragments; 3) surgical debridement for bone infection; 4) surgical excision of necrotic bone; and 5) surgical trimming at a fracture or fracture nonunion site to improve the surface characteristics.[5]

Segmental bone defects associated with fractures or fracture nonunions may have circumferential (complete) bone loss or partial (incomplete) bone loss. These defects may be managed using a variety of treatments. The treatment methods fit into three broad categories including: 1) static methods, 2) acute compression methods, and 3) gradual compression methods.

Circumferential Bone Loss: Static Treatment Methods

Static treatment methods fill the defect between the bone ends. When using static methods, the proximal and distal ends of the fracture or nonunion site are fixed using orthopaedic hardware (internal or external fixation). Static methods for treating bone defects include the use of: 1) autogenous cancellous or cortical bone grafts; 2) vascularized autografts; 3) bulk or strut cortical allografts; 4) mesh cage-bone graft constructs; and 5) synostosis techniques. A variety of static treatment methods using internal and external fixation have been well described elsewhere.[5]

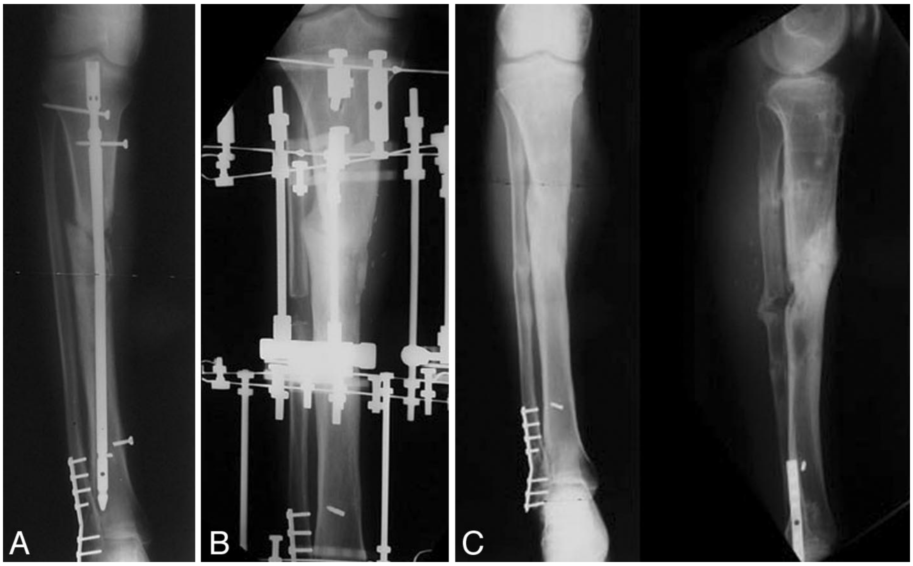

FIG. 7. Associated infection of bone/nondraining quiescent infections. **(A)** Anteroposterior radiograph of a 19-year-old man referred in 15 months following his injury. The patient had a history of purulent drainage at the insertion site of the nail 10 months prior and our workup was suspicious for chronic infection based on nuclear medicine studies and an elevated sedimentation rate. **(B)** Anteroposterior radiograph following application of the Ilizarov external fixator without open debridement, exposure of the nonunion site, or bone grafting. The Ilizarov mode used was differential distraction to correct the deformity and treat the painful nonunion. **(C)** Final anteroposterior and lateral radiographs showing solid bony union and deformity correction.

Circumferential Bone Loss: Acute Compression Methods

Acute compression methods obtain immediate bone-to-bone contact at the fracture or fracture nonunion site by acutely shortening the extremity. The extent of acute shortening that is possible is limited by the soft tissues (soft tissue compliance, surgical and open wounds, and neurovascular structures). Some authors[13,17,31] have suggested that greater than 2 to 2.5 cm of acute shortening at a nonunion site may lead to soft tissue problems, although others have reported that acute shortening is appropriate for defects up to 7 cm in length.[25] In limbs with paired bones, partial excision of the unaffected bone is needed to allow compression across the affected bone. For example, partial excision of the fibula shaft (when the fibula is intact) is necessary to allow compression and shortening of the tibia.

Immediate bone-to-bone contact with acute compression across a segmental defect begins the process of healing as early as possible. A disadvantage of acute compression at segmental defects is the resulting functional consequences from foreshortening of the extremity. In the upper extremity, up to 3 to 4 cm of foreshortening is well tolerated. In the lower extremity up to 2 cm of foreshortening may be treated with a shoe lift. Many patients poorly tolerate a shoe lift for 2 to 4 cm of shortening and most do not tolerate greater than 4 cm of foreshortening. Therefore, many patients undergoing acute shortening with compression across the segmental defect will require a lengthening procedure of the ipsilateral extremity or a foreshortening procedure of the contralateral extremity. These limb length equalization procedures can be performed concurrently with, or sequentially following, the acute compression (shortening) procedure.

Acute compression may be applied using various internal or external fixation devices. Because of its strength and versatility, the Ilizarov method is an excellent treatment option for acute compression applications. The Ilizarov method is also useful in that it allows for restoration of limb length via a corticotomy with lengthening at another site of the bone following compression at the site of injury (bifocal treatment). Bifocal compression-distraction lengthening involves acute (or gradual) compression across the site of bony injury with lengthening through an adjacent corticotomy. This method is applicable for fractures or fracture nonunions associated with foreshortening.

Circumferential Bone Loss: Gradual Compression Methods

Gradual compression techniques using the Ilizarov method include simple monofocal gradual compression (shortening) or bone transport. Neither gradual monofocal compression nor bone transport is associated with the potentially severe soft tissue and wound problems associated with acute compression. However, gradual monofocal compression and bone transport are both associated with malalignment at the docking site (the most extreme case being when the proximal and distal fragments completely miss each other), whereas acute compression is not.

Monofocal Compression. When the chosen method of treatment for circumferential bone loss following failed internal fixation is monofocal gradual compression, the Ilizarov external fixator is constructed to allow

FIG. 8. Circumferential bone loss/bone transport. **(A)** Early anteroposterior radiograph prior to presentation shows interfragmentary screw fixation of a high-energy distal tibial fracture. As might have been predicted, this limited fixation approach did not result in an optimal result. **(B)** Anteroposterior presenting radiograph of a 79-year-old man with an infected distal tibial nonunion with gross purulent drainage and infection involving the entire talus. **(C)** Anteroposterior radiograph showing the progress of bone transport of the tibia into the calcaneus for attempted fusion using the Ilizarov method and bone transport. Note the early proximal tibial regenerate and the large circumferential bony defect distally. **(D)** Anteroposterior and lateral radiographs showing the final result. Note that even in a 79-year-old man, massive regeneration of bony tissue using bone transport is possible. The lateral radiograph shows solid union between the tibia and calcaneus. This patient has regained full ambulatory status in a rocker bottom shoe without the need for any other ambulatory aids and has excellent painless function.

for compression in increments of 0.25 mm. Slow compression at a rate of 0.25 mm to 1.0 mm per day is applied in one or four increments, respectively. When a large defect exists, compression is applied at a rate of 1.0 mm per day; as the fragments approach bony contact, the rate is slowed to 0.25 mm to 0.5 mm per day. As discussed above, compression in limbs with paired bones necessitates partial excision of the unaffected bone.

Bone Transport. When the chosen method of treatment for circumferential bone loss following failed internal fixation is bone transport, the Ilizarov external fixator is constructed to allow for bone transport at a rate ranging from 0.25 mm every other day to 1.5 mm per day (Fig. 8). The transport is typically started at the rate of 0.5 mm to 0.75 mm per day in two or three increments, respectively. The rate is often adjusted (increased or decreased) based on the quality of the bony regenerate as viewed on serial plain radiographs.

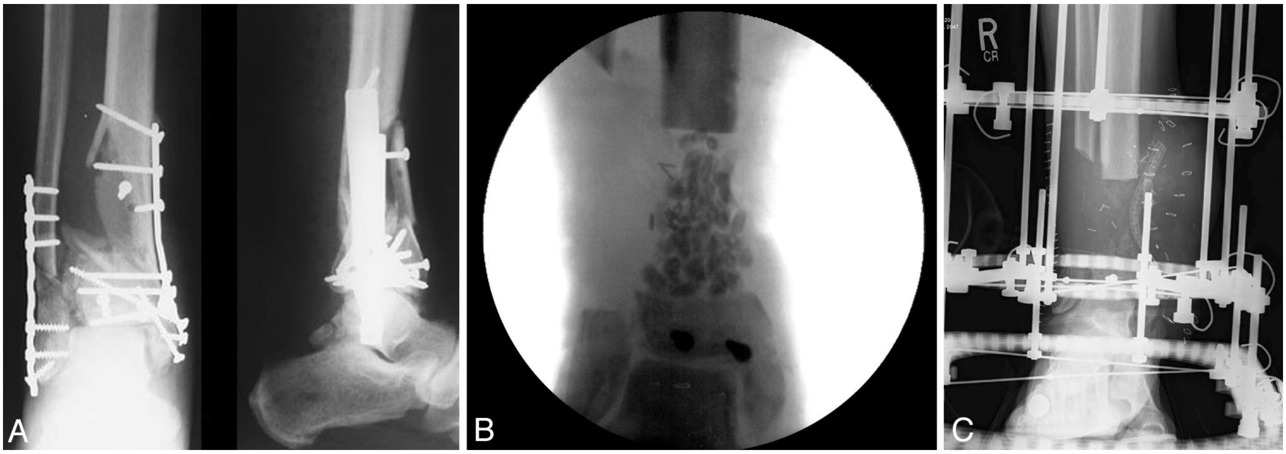

FIG. 9. Partial bone loss. **(A)** Anteroposterior and lateral presenting radiographs of a 53-year-old man following multiple failed attempts at treatment after a severe right distal tibia fracture. The patient presented with this infected distal tibial nonunion with a large partial segmental bone defect following plate and screw fixation. **(B)** Anteroposterior radiograph showing the residual following bony debridement to two opposing flat surfaces and placement of antibiotic beads. **(C)** Anteroposterior radiograph showing the large circumferential segmental defect on postoperative day one with a planned reconstruction via Ilizarov bone transport.

Bone transport (bifocal distraction-compression transport) involves the creation of a corticotomy (usually metaphyseal) at a site distant from the nonunion. The bone segment produced by the corticotomy is then transported toward the nonunion site (filling the bony defect) at a gradual rate. The compression produced by the transported segment arriving at the docking site is successful in obtaining bony union in many cases. Occasionally bone grafting with marrow or open bone graft is required.

The bone formed at the corticotomy site in bone transport is formed under gradual distraction through the process of distraction osteogenesis.[2,3,12,15,22] The mechanism of bone formation in distraction osteogenesis is a result of increased vascularity and cellular proliferation. In a study of dogs undergoing distraction osteogenesis, Aronson[1] reported that blood flow at the distraction site increased nearly ten-fold relative to the control limb, peaking about 2 weeks after surgery. The distal tibia, remote from the site of distraction, also showed a similar pattern of increased blood flow. The mechanical tension-stress effect of distraction is known to cause neovascularity and cellular proliferation in bone and other tissues.

The success of distraction osteogenesis depends on a variety of mechanical and biologic requirements. First, the corticotomy or osteotomy must be performed using a low-energy technique. Second, corticotomy or osteotomy in the metaphyseal or metadiaphyseal region is preferred over diaphyseal sites because of the superior potential for regenerate formation. Third, a very stable external fixator construct, such as that available in the Ilizarov method, is required to promote good bony regenerate. Fourth, a latency period prior to beginning distraction of 7 to 14 days is recommended, depending on various patient characteristics. Fifth, the distraction phase is classically performed at a rate of 1.0 mm per day in a rhythm of 0.25 mm of distraction performed 4 times per day. Since some patients make bony regenerate more slowly, the rate and rhythm of distraction should be carefully controlled by the treating physician, who can monitor the progression of the regenerate on plain radiographs. Sixth, following distraction, maturation and hypertrophy of the bony regenerate must be allowed to occur during the consolidation phase. The consolidation phase is generally two to three times as long as the number of days of the distraction phase, but this varies widely among patients.

For both gradual compression and bone transport, favorable surface characteristics at the docking site (site of injury) greatly improve the chances of rapid healing. When poor surface characteristics are present, open trimming is recommended. When open trimming is performed at the time of the initial procedure, the docking site can be bone grafted if the anticipated time to docking is approximately 2 months or less (such as a 6 cm defect treated with gradual shortening or bone transport at a rate of 1.0 mm per day). If the time to docking will be significantly greater than 2 months (such as for larger defects), two options exist. First, gradual compression or transport can be continued even after bony touchdown at the docking site is seen on plain radiographs. Continued compression at a rate ranging from 0.25 mm per week to 0.25 mm per day at the docking site is seen clinically and

FIG. 10. Severe irreducible deformity with a hypertrophic nonunion. **(A)** Early anteroposterior and lateral radiographs prior to presentation show plate and screw fixation of a high-energy open femur fracture associated with a vascular injury which required repair. **(B)** Presenting radiograph 10 months following the injury shows a hypertrophic nonunion with progressive hardware failure and the development of a coronal plane deformity. **(C)** Anteroposterior and lateral radiographs in the Ilizarov external fixator. This patient was treated with differential lengthening (distraction) for deformity correction and nonunion treatment. **(D)** Final radiographic appearance shows solid bony union with correction of the deformity.

radiographically as bending of the fixation wires, indicating that the rings are moving more than the proximal and distal bone fragments. Second, the docking site can be opened prior to bone contact (usually when the defect is approximately 1 to 2 cm), the proximal and distal surfaces can be freshened up, and the defect can be bone grafted. Gradual compression or transport then proceeds into the graft material.

The literature is not helpful in clarifying whether bone grafting the docking site significantly decreases the time to healing. A useful alternative to open bone grafting is percutaneous marrow injection at the docking site. This technique is minimally invasive and quite effective. I use percutaneous marrow injection for patients at risk for persistent nonunion. I reserve open bone grafting of the docking site for: 1) those patients who fail to demonstrate radiographic evidence of progression to healing despite 4 months of continued compression after bony touchdown; 2) those patients at greatly increased risk of persistent nonunion at the docking site (those patients who have several contributing factors for nonunion;[5] and 3) those patients with poor surface contact at the docking site (these patients require trimming of the bone ends to improve the surface characteristics).

Partial Bone Loss

By virtue of their architecture (point to point contact), nonunions with partial segmental defects are not readily amenable to many of the treatment strategies that have been discussed. These types of defects are most commonly treated with a static method, such as autologous cancellous bone grafting with internal or external fixation. As the segment of partial bone loss increases in length, the chances for successful bony union using conventional bone grafting techniques decreases (Fig. 9). In cases with a large ($>$ 6 cm) segment of partial (incomplete) bone loss, the treatment options are: 1) "splinter (sliver) bone transport," 2) surgical trimming of the bone ends to enhance surface characteristics followed by an acute or gradual compression method, or 3) strut cortical allogenic bone grafting.

Osteopenic States

The thin wires used in the Ilizarov method provide remarkably good purchase in osteopenic bone. The use of 1.8 mm tensioned wires at high crossing angles (up to 90°) provides very good stability for the site of bony injury even in very weak bone. The stability of the Ilizarov external fixator can be improved for use in osteopenic bone by the use of olive wires, which discourage translational moments at the wire-bone interface. The use of a washer at the olive wire-bone interface also helps to distribute the load and prevent erosion of the olive into the bone.

Severe Irreducible Deformity with a Hypertrophic Nonunion

A severe irreducible deformity with a hypertrophic (stiff) nonunion following failed internal fixation is best treated by gradual deformity correction (Fig. 10). The advantage of the Ilizarov method in these cases is that osseous integration can be achieved simultaneously during the gradual deformity correction. Furthermore, the Ilizarov method allows not only for simple compression and distraction, but also for differential compression and distraction to allow for correction of complex deformities. In addition, the Ilizarov method does not require large soft tissue dissection as would be required with deformity correction using internal fixation techniques.

Distraction of the abundant fibrocartilaginous tissue in hypertrophic nonunions stimulates new bone formation.[7,16,24,30] Distraction using the Ilizarov method results in bony healing in a high percentage of such cases,[7,30] although the exact biologic mechanism remains obscure.

CONCLUSION

Treatment with internal fixation fails for a variety of reasons, and revision internal fixation using the same or a different internal fixation technique may be successful. In certain cases, however, the Ilizarov method may be the preferred treatment strategy following failed internal fixation. The Ilizarov method offers many advantages for treatment of fracture or fracture nonunion following failed internal fixation. Several modes of treatment are available with the Ilizarov method, including monofocal, acute, or gradual compression and bone transport (bifocal treatment). The Ilizarov method provides excellent mechanical stability, biologic stimulation at the site of bony injury, and the ability to generate new bone tissue through distraction osteogenesis. Cases of fracture or fracture nonunion that have failed internal fixation that respond well to the Ilizarov method include those: 1) with multiple previous attempts using internal fixation; 2) with small or numerous bony fragments; 3) with bone infection; 4) with a bony defect; 5) with osteopenic states; and 6) with a stiff (hypertrophic) nonunion associated with a severe irreducible deformity.

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