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Editors

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Chapter 13

Nonunions and Malunions

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Introduction

Nonunions are a significant clinical problem in the United States. It is estimated that 2% to 10% of all tibial fractures do not achieve union. This results in a large number of procedures performed to treat nonhealing fractures, increased morbidity for patients, and significant additional costs.

Fracture union occurs when the bone is repaired to a degree that it is mechanically able to function like the original bone. The patient experiences no pain, and there is clinical stability at the fracture site. Fracture unions are accompanied by radiographic evidence of healing.

A delayed union is a fracture that, although progressing toward union, has not healed in the expected amount of time for a comparable fracture. A nonunion is a fracture that will not heal. A nonunion is the result of an arrest of the repair process and radiographic or clinical evidence of healing has not been seen for months. Nonunions may have some clinical stability because they will have cartilage or fibrous interposition instead of bone. Although nonunions cannot be predicted, some fractures are destined to evolve to nonunion from the beginning of treatment.

Etiology

The etiology of a fracture nonunion is multifactorial. There is an interaction between fracture-related issues, the medical condition and habits of the patient, and the treating surgeon.

Not all fractures are created equally. Fractures result when the energy imparted to the bone during an injury exceeds the mechanical strength of the bone. Fractures disrupt not only the bone and its internal architecture, but the surrounding soft tissues as well. Traumatic stripping of the periosteum and disruption of the surrounding muscle and skin can deprive the fracture of the blood supply essential to healing. The more energy that is imparted to the limb, the greater this disruption.

Fracture Factors

Factors related to the fracture itself include the bone involved and the portion of the bone that is injured. Bones such as the talus, the metaphyseal-diaphyseal junction of the fifth metatarsal, and the scaphoid have well-known blood supplies. Some areas, such as the distal femur, have a robust blood supply, whereas others, such as the distal tibia, are relatively lacking blood supply. Fractures with bone loss, either bone that is lost at the scene of injury or to surgical débridement, are nonunions in evolution, and they require a staged approach to reconstruction. The degree of soft-tissue injury, whether in an open or closed fracture, also plays a role in whether a fracture achieves union. Open fractures are indicative of a high degree of soft-tissue devitalization, and they are a source of contamination and potential infection. High-grade soft-tissue injuries in closed fractures can also result in devitalized bone and altered healing.

Host Factors

Host factors also play a major role in fracture healing. Although young, healthy patients generally heal with little difficulty, those with preexisting medical conditions can have a decreased ability to recover from injury. Patients with chronic disease such as diabetes, heart disease, and chronic obstructive pulmonary disease do not fare as well. Patients who are immunosuppressed, for whatever reason, be it the result of rheumatoid disease, malignancy, malnutrition, human immunovirus, or steroid use will heal slower. Smoking has been shown to decrease the rate of fracture healing in many studies.

Surgical Factors

Surgery also greatly influences the ability of fractures to heal. Fractures require a stable mechanical environment to unite. Fractures treated with constructs that provide relatively nonrigid immobilization such as casts, external fixation, or bridge plating heal via secondary bone healing with the formation of callus.[1] Essential to this form of treatment is stable fixation that allows some motion at the fracture site. Inadequate fracture fixation, whether from a poorly applied cast or a poorly planned external fixator, will lead to too much motion and inadequate healing. Fractures treated with rigid internal fixation rely on primary bone healing to unite. In this type of bone healing, areas of bone undergo direct remodeling by cutting cones, and adequate compression is essential to success. Reductions that leave a gap, malposition the fragments, or leave soft tissue interposed often lead to slow healing. Excessive iatrogenic stripping of the bone adds to the soft-tissue injury inherent in the fracture, leading to a suboptimal biologic environment, slow healing, and possible infection. Infrequent follow-up, premature weight bearing, or surgeon inattention to detail may also contribute to a less desirable result.

For most nonunions, the exact cause is difficult to pinpoint. Most are not the result of one clear-cut cause, but rather a combination of many of the factors discussed previously. The cause of many nonunions is never known. Surgeons who treat these challenging problems should attempt to identify and reverse the contributive factors they can control. Mechanical stability should be provided, soft-tissue envelopes should be respected to preserve blood supply, the biology of the fracture should be augmented when possible, and bone loss should be managed with shortening, grafting, or bone transport techniques.

Evaluation

The evaluation of a patient with a nonunion, just as with a patient with an acute injury, requires a thorough assessment of more than just the fracture pattern and the radiographs. The personality of the fracture must be determined. This involves a complete history of the events of the injury, the fracture, the host, the treating physician, and the institution at which the treatment will occur. Only with this kind of analysis can adequate preoperative planning be done that will optimize the chance for success.

Patient History

A complete patient history is essential. The mechanism of the fracture must be determined as well as that of other associated injuries, such as those involving the head, chest, or abdomen. Was the initial injury open or closed? Was there a high-energy mechanism such as a motorcycle accident or a lower-energy trip and fall? Were there any neurovascular issues present at the time of the initial injury or after treatment? A complete history of the initial treatment and all other previous treatment is necessary. A determination of the type and number of previous surgeries is essential, as is the presence and treatment of previous infection. If there is retained hardware at the fracture site, old surgical notes can be helpful in identifying its type and manufacturer for planned removal.

A complete picture of the patient must also be developed. A thorough past medical and surgical history must be obtained, as well as a list of current medications, allergies, and social habits. Have previous fractures healed in a timely fashion? Patients with recreational drug habits or other substance abuse may have compliance issues. Smokers are at risk because of the well-documented relationship between nicotine use and delayed fracture healing.[2] The occupation of the patient is also important because treatment that requires a non–weight-bearing gait will require more time off from work for a laborer than a patient with a more sedentary occupation.

Physical Examination

A complete musculoskeletal examination is important. Examination of the patient's other extremities will provide clues as to additional disabilities that may play a role in mobility and later rehabilitation. Examination of the nonunited segment includes an inspection for gross deformity and overall limb alignment. Gross limb length can be measured, and if the patient is ambulatory, the gait pattern should be assessed. The skin should be inspected for the presence, location, and healing status of previous open wounds and incisions. The presence or absence of lymphedema or venous stasis should be noted. If previous external fixators have been in place, the condition of the old pin sites should be examined. A complete neurovascular examination should be performed. The presence and character of the pulses should be noted. Patients with suspected dysvascular limbs should undergo more thorough testing, including transcutaneous oxygen tension and ankle-brachial indices. Existing nerve deficits can be examined and tested by electromyography to determine the likelihood of recovery. The fracture site should be checked for tenderness to manual stress, as well as the presence of gross or subtle motion. The motion of adjacent joints should be examined. If joint contracture is present, it should be determined if it is caused by soft-tissue contracture, heterotopic ossification, or both.

Radiographic Evaluation

Radiographic evaluation includes true AP and lateral radiographs of the problem limb segment orthogonal to the "normal" portion of the limb. If deformity or limb length issues are suspected, special radiographs are required. Long leg alignment films and scanograms should be obtained. Comparison films of the contralateral leg are helpful in determining normal alignment, and population norms can be used if the problem is bilateral. Although CT with reconstructions can be helpful in analyzing subtle nonunions, it can be difficult to interpret with fracture fixation devices in place. Plain tomography can be very helpful in these instances. If infection is suspected, a combined bone scan and radiolabeled white cell study can help differentiate bone turnover from active infection. Sinograms can be used to determine whether chronic wounds communicate with the fracture site. MRI can be helpful in the evaluation of bone for infection or the assessment of adjacent joints, but it is not commonly used in the evaluation of nonunions.

Laboratory Evaluation

Laboratory studies can complete the clinical assessment of the patient. In addition to routine preoperative tests and blood cell counts, patients suspected of having infection should have their erythrocyte sedimentation rate and C-reactive protein level assessed. Patients suspected of being malnourished should have a complete nutritional panel drawn, including liver enzymes and total protein and albumin levels.

Preoperative Planning

The last aspect of the evaluation of the personality of the fracture is an assessment of the surgeon and the treating facility. Preoperative planning should include timely and appropriate consultation with plastic or microvascular surgeons if flaps or wound issues are anticipated; vascular surgeons should be consulted if poor vascularity is suspected. The patient's primary care physician can help with the treatment of chronic medical conditions. Surgeons should honestly examine whether they have the training, skill, patience, and experience necessary to treat a complex nonunion. To assess the treating facility, it is important to determine whether the correct equipment is in the hospital or available to be brought in, whether there is experienced nursing and surgical assistance available, and whether the anesthesia staff can address the needs of a sick patient.

At the end of the evaluation, orthopaedic surgeons should create a problem list in anticipation of preoperative planning. This list should include pertinent positive factors about the patient's social condition and history, physical examination, bone, skin, and retained hardware. The consultations required should also be listed, as well as the equipment required for the surgical procedure. A preoperative plan should be prepared and drawn out in detail in all but the simplest of conditions (Figure 1).

Classification

Unlike acute fractures, there is no single definitive classification system for nonunions. Nonunions can be classified on the basis of anatomy, the presence or absence of infection, healing potential, or stiffness. More than one method of describing the nonunion is often helpful in determining a treatment plan.

The first issue to resolve is whether the fracture is a delayed union or a true nonunion. A delayed union may progress to a successful union over time, whereas a true nonunion will require intervention to achieve union. This is not a trivial issue to resolve. Although most nonunions will be diagnosed if the surgeon waits long enough, it is imperative to identify fractures that are falling behind in the healing process as soon as possible to shorten the overall treatment time and restore the patient to full function. Delaying intervention for an arbitrary length of time before calling a fracture a nonunion can result in more disability, more time off work, and greater psychologic stress for the patient. As soon as slow healing is identified, a frank discussion of the possibility of nonunion should be had with the patient about the need for further treatment. Many patients will opt for early intervention when it means an earlier return to work or recreational activities.

Nonunions are also classified by their anatomic location. Diaphyseal nonunions have relatively less biologic potential because they involve cortical bone, but they are amenable to a variety of treatment methods, including intramedullary nails, compression plating, and external fixation. The goal in this instance is to restore length and axial alignment while achieving fracture union. As the nonunion reaches the metaphyseal region, the goals remain the same, but the options for fixation are more limited. Periarticular nonunions may also be associated with stiff or contracted joints that must be accounted for in the preoperative plan. Nonunions of the articular surface are particularly challenging. Defining the extent of the nonunited segment may require multiple radiographs and CT scans. Step-offs, gaps, and injury to the joint surface may lead to local or global arthritis. Treatment may consist of open reduction and rigid fixation, arthrodesis, or arthroplasty.

Nonunions may be aseptic or infected. Although many studies have shown that bone constructs with adequate stability can heal in the face of infection, the general goal is to convert an infected nonunion into a noninfected nonunion, and then proceed with treatment of the fracture. Because many infected nonunions will have skin breakdown, open wounds, and drainage, the diagnosis is not always obvious. Laboratory studies can be helpful, as can nuclear medicine studies. The patient should be counseled that treatment might involve several staged procedures for hardware removal, débridement of dead bone, soft-tissue coverage, and stabilization. A course of intravenous antibiotics based on the results of thorough deep cultures should be followed by definitive reconstruction. Depending on the extent of the infection and bone resected, this may require a period of months. Failed soft-tissue coverage, failure to eradicate the infection, or failure to obtain union may lead to eventual amputation.

Nonunions can be classified on the basis of their biologic potential. Hypertrophic nonunions are characterized by abundant bone formation, and they are often

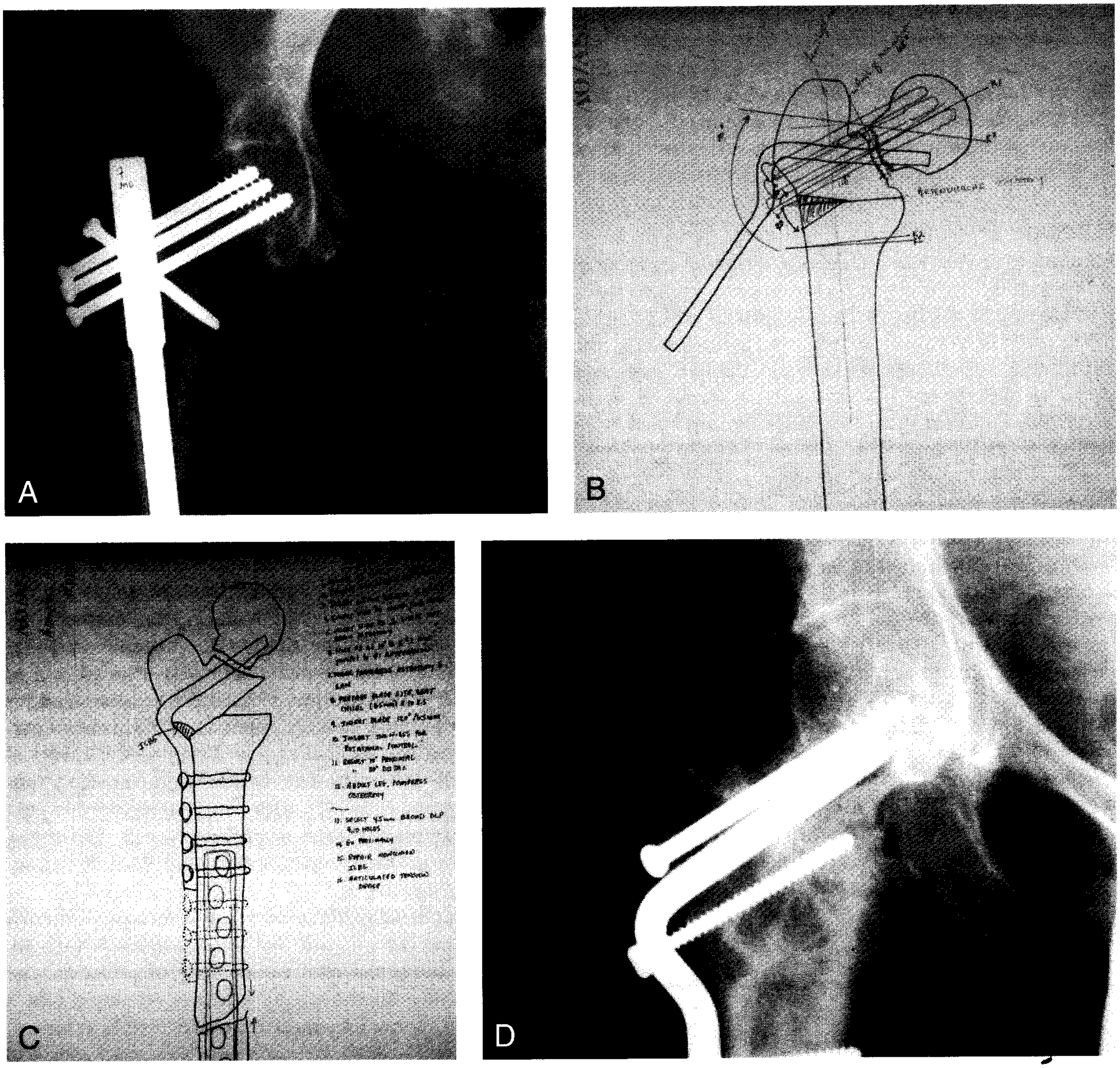
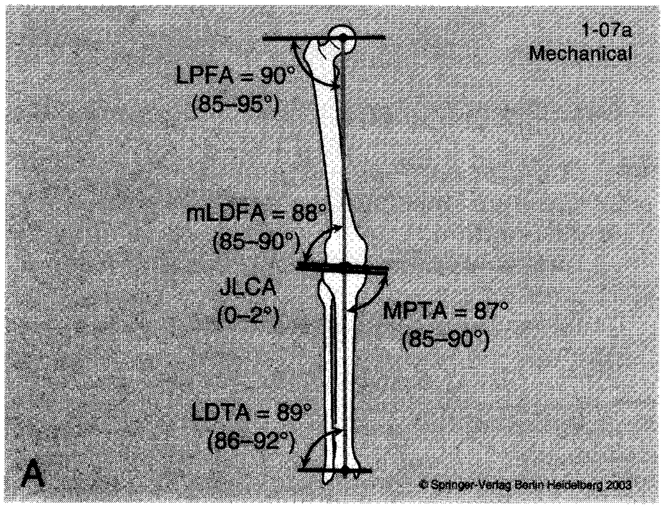
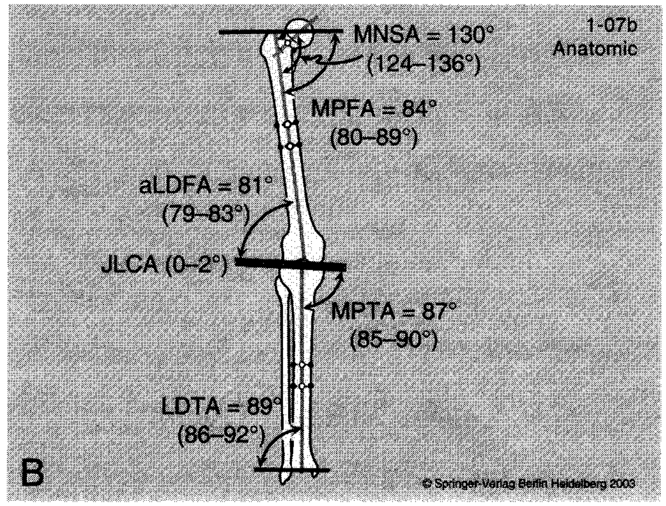


Figure 1 **A,** Radiograph of a 37-year-old man 7 months after an ipsilateral femoral neck and shaft fracture. The femoral head is visible. **B,** Illustration of the preoperative plan for a valgus-producing intertrochanteric osteotomy. The osteotomy that will convert the shearing forces at the fracture to compressive forces has been calculated. **C,** The final drawing illustrating and listing the step-by-step surgical plan for the osteotomy. By planning on paper preoperatively, orthopaedic surgeons can minimize mistakes and delays at the time of surgery. **D,** Radiograph obtained after the union of the osteotomy. The alignment demonstrated here is essentially that found on the preoperative plan.

referred to as having the appearance of an elephant's foot. In general, they are stiff and relatively stable. Patients are often able to bear weight with pain when they have a hypertrophic nonunion. These nonunions have excellent blood supply and biologic potential and often require only the addition of fracture stability to unite. Atrophic nonunions, conversely, have little biologic potential. Atrophic nonunions are often the result of open fractures or previous surgical procedures that have caused a disruption of the normal vascular supply to the bone. A cessation of the regeneration process has occurred along with resorption of the bone ends and sometimes capping off of the endosteal canal of the bone. These nonunions are mobile; patients usually are unable to bear weight and may require external immobilization for comfort. A special type, the atrophic nonunion, is a true pseudarthrosis in which a false joint has been created between the two ends of the bone. These fractures require biologic stimulation in addition to skeletal stability. Bone grafting and other adjuvants often play a role in their treatment. Oligotrophic nonunions are somewhere in between these two extremes. They have





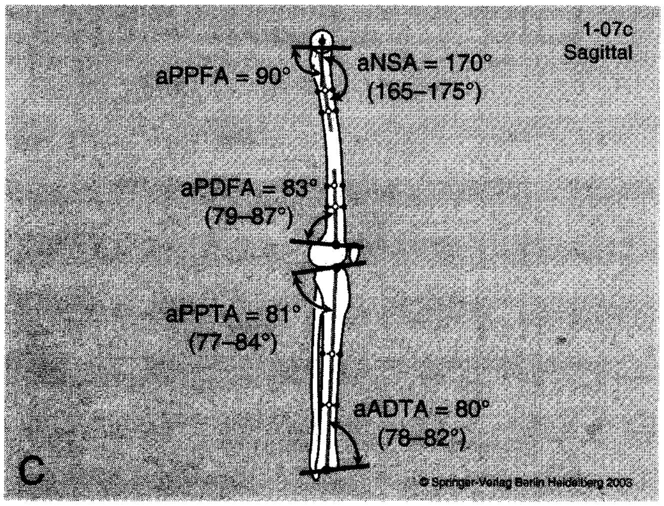


Figure 2 Normal mechanical axis values. **A,** Frontal plane joint orientation angle nomenclature and normal values relative to the mechanical axis. LPFA = lateral proximal femoral angle, mLDFA = lateral distal femoral angle relative to the mechanical axis, JLCA = joint line convergence angle, MPTA = medial proximal tibial angle, LDTA = lateral distal tibial angle. **B,** Frontal plane joint orientation angle nomenclature and normal values relative to the anatomic axis. MNSA = medial neck shaft angle, MPFA = medial proximal femoral angle, aLDFA = lateral distal femoral angle relative to the anatomic axis. **C,** Sagittal plane joint orientation angle nomenclature and normal values relative to the anatomic axis. aPPFA = anatomic posterior proximal femoral angle, aNSA = anatomic neck shaft angle, aPDFA = posterior distal femoral angle relative to the anatomic axis, aPPTA = posterior proximal tibial angle relative to the anatomic axis, aADTA = anterior distal tibial angle relative to the anatomic axis. *(Reproduced with permission from Paley D:* Principles of Deformity Correction. *Berlin, Germany, Springer-Verlag, 2002.)*

very little callus formation, but the bone ends are vital. They often require both biologic and mechanical augmentation.

Deformity

Deformity is an important issue with regard to both nonunions and malunions. With malunions, the deformity is the sole problem. With nonunions, deformity is often a crucial aspect of the problem. Although with nonunions, the treatment goals are achievement of bony union and correction of the deformity, correction of the deformity is the more central issue. To achieve bony union, the deformity must be corrected first because it is a key mechanical factor that is contributing to the nonunion. In the presence of deformity, the load during weight bearing creates a bending moment at the nonunion site—an unfavorable mechanical situation. With normal limb alignment, weight bearing achieves compression across the nonunion—a favorable mechanical situation.[3-6]

Limb deformity is a more important factor in lower extremities than upper extremities. Studies have suggested that tibial malunions are associated with arthrosis of the knee and ankle.[7] The imprecision of such an analysis is that the absolute amount of angular deformity in the tibia is but one factor. The overall deformity of the limb is affected by the level of deformity, magnitude of angulation, translation, rotation, and shortening. For example, the same 7° angular deformity of the tibia will have a different effect on mechanical axis deviation of the knee and ankle depending on the level of the fracture and any associated translation. In some patients, angulation and translation can have an additive effect and in others they can cancel each other out, resulting in very little limb axis deformity.

Normal mechanical limb alignment is illustrated with a mechanical axis line drawn from the center of the hip to the center of the ankle. The location of this line relative to the center of the knee joint defines the mechanical axis deviation (MAD). Normal coronal plane alignment has a MAD of 0 to 8 mm medial to the center of the knee. The alignment of each bone can then be analyzed with joint orientation angles. Mechanical and/or anatomic analysis can be used (Figure 2). Al-

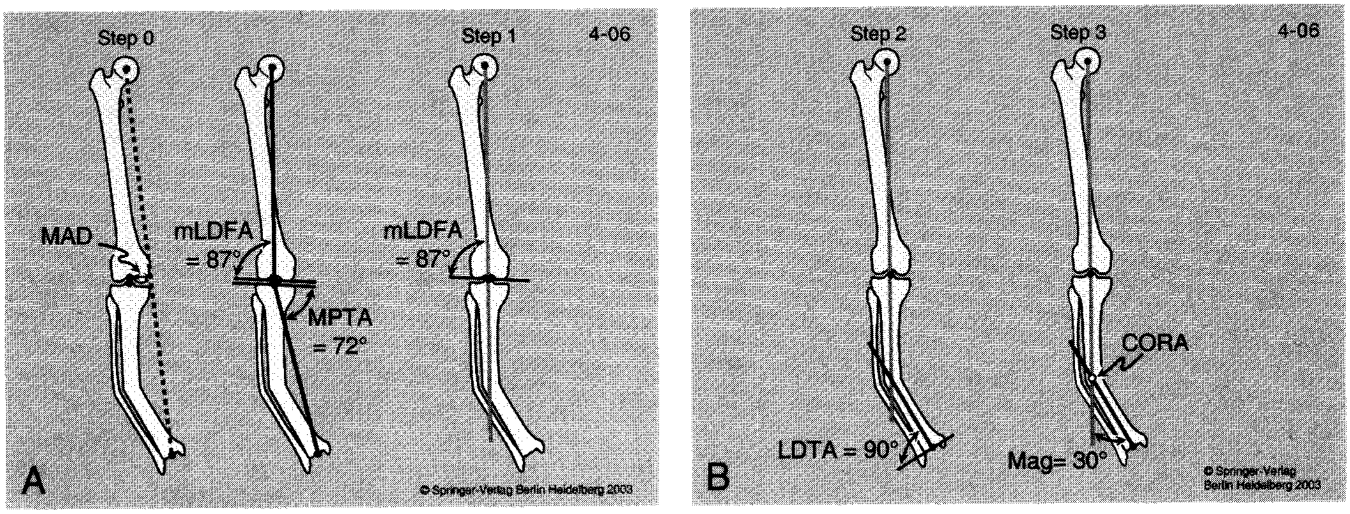


Figure 3 Calculation of diaphyseal deformity. **A,** Step 0: MAD medial to center of knee represents varus deformity. Normal lateral distal femoral angle (LDFA) shows absence of femoral deformity. Abnormal medial proximal tibial angle (MPTA) shows that the tibia is the source of the deformity. Step 1: The proximal mechanical axis line is extended from the normal femur. **B,** Step 2: The distal mechanical axis line is drawn. Step 3: The intersection of the proximal mechanical axis line and the distal mechanical axis line is the center of rotation and angulation (CORA), which identifies the location and magnitude of the deformity in the diaphysis of the tibia. *(Reproduced with permission from Paley D:* Principles of Deformity Correction. *Berlin, Germany, Springer-Verlag, 2002.)*

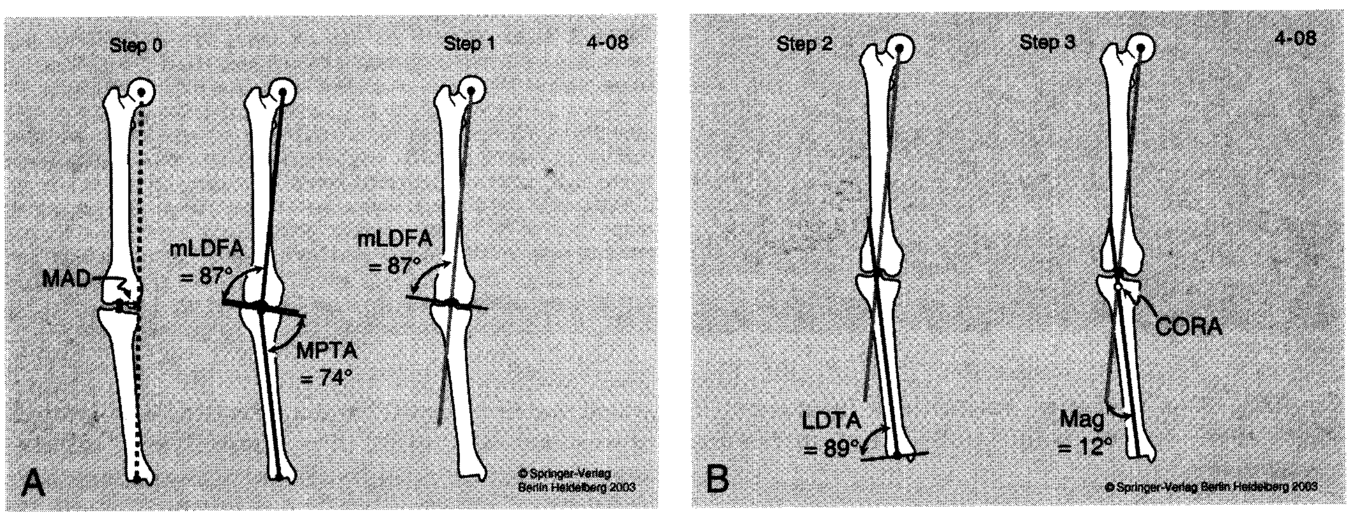


Figure 4 Calculation of metaphyseal deformity. **A,** Step 0: MAD is medial to the center of the knee, showing that there is a varus deformity. The femur has no deformity (normal lateral distal femoral angle [LDFA]). The tibia has varus deformity (abnormal medial proximal tibial angle [MPTA]). Step 1: The proximal mechanical axis line is extended from the normal femur. **B,** Step 2: The distal mechanical axis line is drawn. Step 3: The intersection of the proximal mechanical axis line and the distal mechanical axis line is the center of rotation and angulation (CORA), which identifies the location and magnitude of the deformity in the metaphysis of the proximal tibia. *(Reproduced with permission from Paley D:* Principles of Deformity Correction. *Berlin, Germany, Springer-Verlag, 2002.)*

though this type of analysis may be useful for a patient with mid-diaphyseal deformities (Figure 3), it is particularly useful for those with metaphyseal deformities or double level deformities (Figure 4). The location and magnitude of the deformity is identified by drawing antegrade and retrograde bone axis lines. The location of the intersection is the center of rotation and angulation. The angle between these lines is the magnitude of the deformity. If the center of rotation and angulation is not located at what seems to be the old fracture site, it usually means that there is associated translation deformity (Figure 5).

Analysis is done in the coronal plane using an AP radiograph and in the sagittal plane using a lateral radiograph. When deformity is present in both planes, it is consistent with an oblique plane deformity. It is actually one deformity in an oblique plane. For example, a tibia with varus and procurvatum has an oblique plane deformity with the apex of deformity in the anterolateral plane (Figure 6). The axis of correction is 90° to that plane. Gradual corrections can be performed with circular frames. Although the classic Ilizarov frame works well in these patients, the Ilizarov/Taylor Spatial Frame (Smith & Nephew, Memphis,

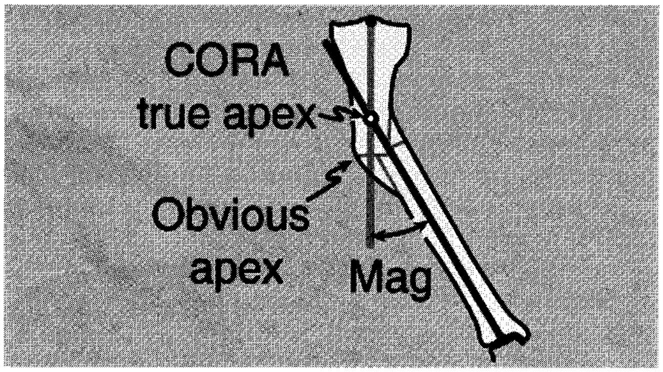


Figure 5 When the center of rotation and angulation (CORA) is not at the obvious malunion site, there is often associated translation deformity. *(Reproduced with permission from Paley D:* Principles of Deformity Correction. *Berlin, Germany, Springer-Verlag, 2002.)*

TN) simplifies the correction with the help of a computer program.[5,8] Acute corrections and internal fixation can also be done to correct deformities.

Limb-length discrepancy and limb alignment can be measured from a weight-bearing long leg radiograph. The short leg is placed on blocks to level the pelvis, and the height of the blocks is recorded. This can be done with the patient using crutches if necessary. A supine scanogram can also be used to measure limb-length discrepancy, but this is not useful for alignment analysis. Rotational deformity is best assessed on clinical examination with the patient in the prone position. Thigh-foot axis is used to assess rotational deformity of the tibia. A rotational profile of the femur is used to assess rotational deformity in the femur. CT can also be used for this purpose. CT cuts at the proximal femur, distal femur, proximal tibia, and distal tibia allow analysis of rotational deformity.[4]

Choosing a Treatment Method

Because the specific treatment of nonunion and malunion of all bones of the skeleton is a vast topic that is beyond the scope of this chapter, treatment principles that can be applied to all bones will be discussed. Each nonunion and malunion has a unique personality that must be understood to choose an appropriate treatment method. The personality of a malunion is defined by the elements of the deformity, which include location, length discrepancy, angulation, translation, and rotation. Additional factors that should be assessed to help determine the personality of a malunion include time since injury, patient symptoms, and patient age and health, previous hardware, and soft-tissue envelope. Assessment of all of these factors will help the orthopaedic surgeon determine the optimal treatment method. Nonsurgical treatment includes the use of a shoe lift. Surgical treatment includes epiphysiodesis in pediatric patients and osteotomy in adults and children. The tools available include intramedullary rods, plates and screws, and external fixation. The methods include acute or gradual correction.

Epiphysiodesis of a long normal leg can be used to correct limb-length discrepancy in a growing child. A partial growth arrest after trauma leads to progressive angular deformity. To prevent further progressive deformity, the injured growth plate can be completely closed. This procedure can be combined with osteotomy for deformity correction and lengthening as needed.[4]

The personality of the nonunion can be identified by assessing all of the previously discussed factors plus additional characteristics, which include the presence of infection and drainage, bone loss, stability and healing potential of the nonunion, and neurovascular status of the limb. The treatment methods include nonsurgical management with bracing, shoe lift, and noninvasive stimulation with electricity or ultrasound.[9,10] Surgical methods and tools for nonunion repair include bone graft,[11,12] intramedullary rods,[13-19] plates and screws,[20-26] external fixation,[3,5,8,27-32] acute or gradual treatment, and bone transport[3,31] or free fibula grafting.[33-35] Soft-tissue coverage problems can be handled with skin grafts, rotational flaps, free tissue transfer, vacuum-assisted closure device,[36] and soft-tissue transport.[3,31] Amputation reconstruction may also be a primary or secondary treatment option. The experience of the orthopaedic surgeon and the hospital equipment and facilities also help determine treatment.

There are several biologic enhancements to bone healing, including autogenous bone graft, bone graft substitutes,[11] ultrasound, and electricity.[9,10] These are covered in detail in chapter 12. In patients with a delayed union, no infection or deformity, and a stable fixation construct, it is reasonable to try a noninvasive modality such as electricity or ultrasound. Studies have suggested that these modalities enhance bone healing.[9,10]

Bone graft can be used to stimulate the biology of the nonunion.[11,12] In patients with a stable fixation construct and no deformity or infection, bone graft materials can be effective in stimulating union. Bone graft is more typically used in conjunction with surgical repair of the nonunion and stabilization with internal or external fixation. Bone graft should be avoided in patients with infections and should not be used alone in patients with deformities or unstable fixation constructs.

Acute or Gradual Correction

Nonunions or malunions can be treated using either acute or gradual correction. Acute correction can be performed in conjunction with all methods of fixation including plates, intramedullary nails, and external fixation frames. Gradual correction requires the use of special frames or nails. The personality of the problem helps guide the orthopaedic surgeon toward the best method. For example, a tibial malunion with 15° valgus deformity and a 4-cm shortening would be best treated with an

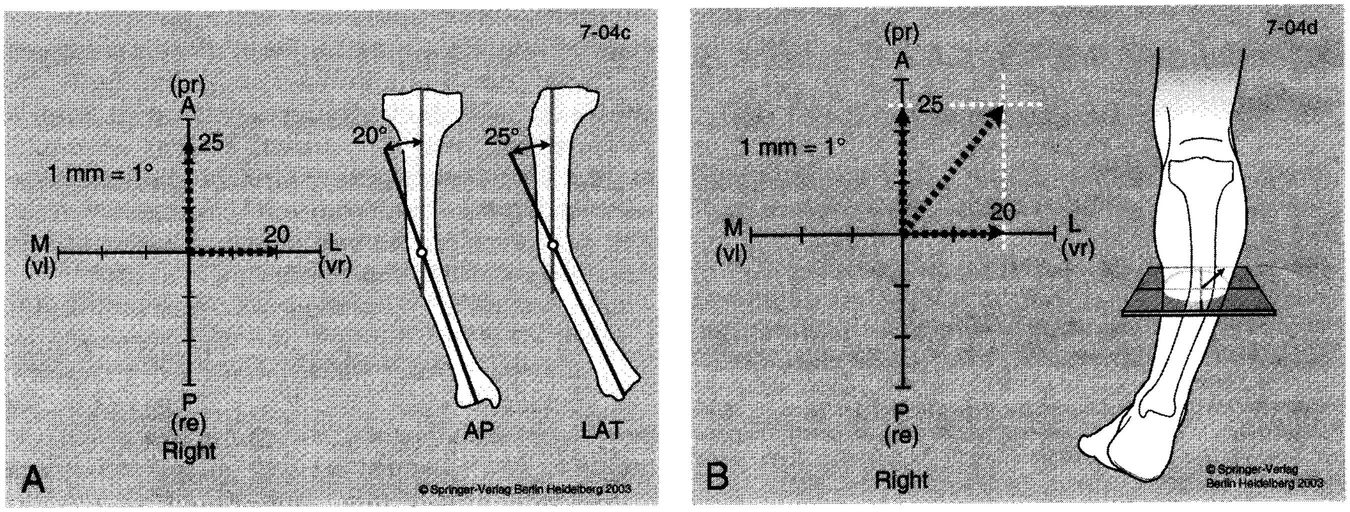


Figure 6 Calculation of oblique plane deformity. **A,** The 20° of varus identified on AP radiograph and the 25° of procurvatum identified on lateral radiograph are graphed as 20 apex lateral and 25 apex anterior. **B,** The resultant vector is the actual magnitude of deformity, with the apex in the anterolateral quadrant. *(Reproduced with permission from Paley D:* Principles of Deformity Correction. *Berlin, Germany, Springer-Verlag, 2002.)*

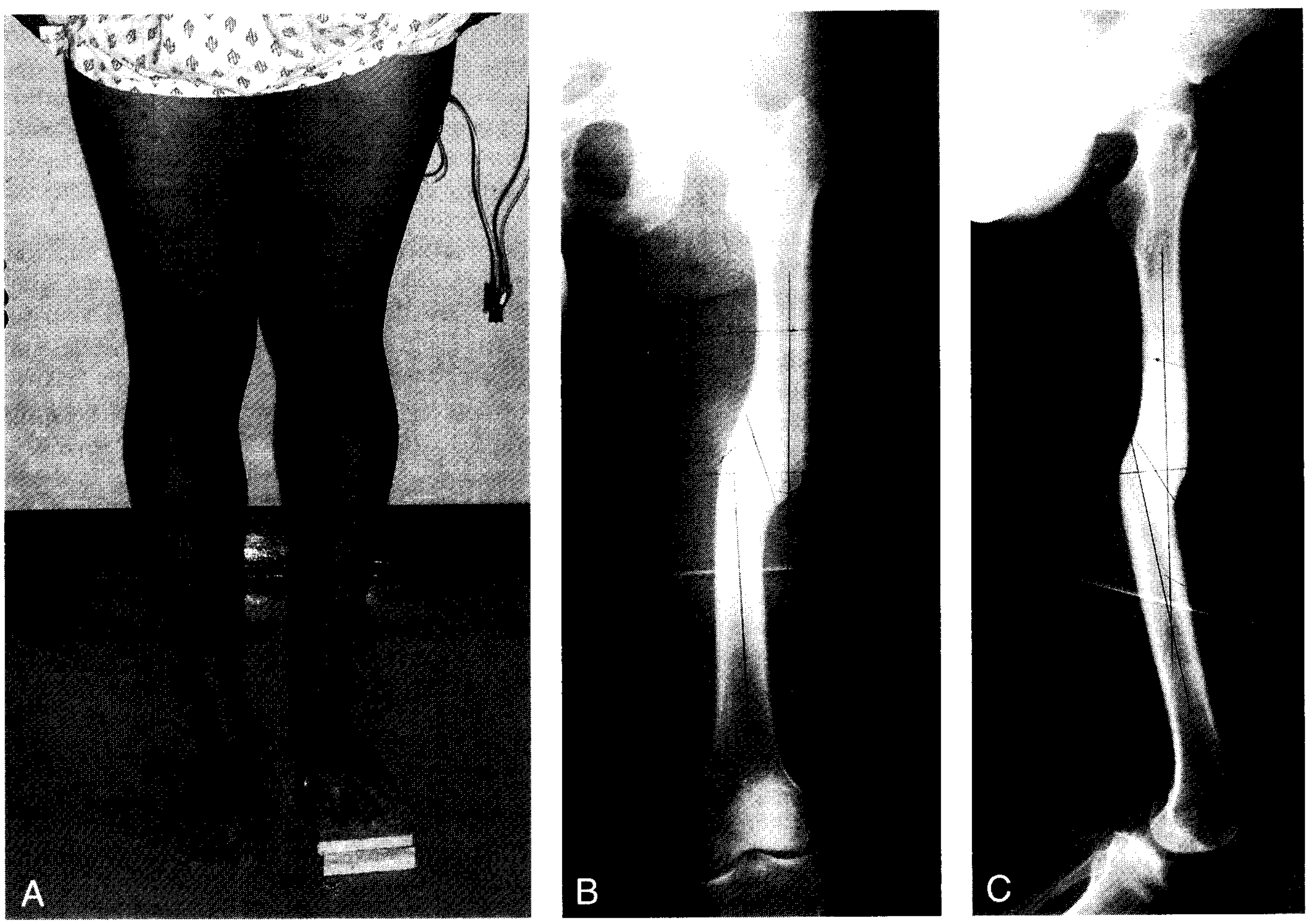


Figure 7 **A,** Preoperative front view photograph shows a patient with 4-cm lower limb shortening. Preoperative AP **(B)** and lateral **(C)** radiographs of the same patient show femur malunion with angular and translational deformity.

osteotomy to gradually correct the angular deformity and lengthen the bone with a specialized external fixation frame. The Ilizarov method is used to gradually correct the complete deformity with distraction osteogenesis. The deformity correction and lengthening may be performed at one level if bone regeneration potential is good. Alternatively, a double-level osteotomy may be performed—one level at the center of rotation and angulation for deformity correction and one level for lengthening in the proximal tibia metaphysis. Gradual correction achieves treatment of shortening and carries less risk of peroneal nerve neurapraxia than if attempted with an acute correction.

The use of plates and intramedullary nails requires an acute correction of angular and translational deformities. Acute correction is particularly useful for patients with modest deformities, mobile atrophic nonunions that are surgically approached and bone grafted, and small bone defects that can be acutely shortened. The principal advantage of acute correction is earlier bone contact for healing and a simpler fixation construct. Acute correction is generally better tolerated in the femur and humerus and less well tolerated in the tibia and ankle because of poor quality soft tissues and risk for neurovascular insult.[3,31]

Gradual correction with a specialized frame is useful for patients requiring large deformity correction, associated limb lengthening, bone transport to treat segmental defects,[3,30] and for stiff hypertrophic nonunion repair.[3,5,8,27,32,37] Gradual correction uses the principle of distraction osteogenesis, which is commonly referred to as the Ilizarov method.[3] Bone and soft tissue are gradually distracted at a rate of approximately 1 mm per day in divided increments. Bone growth in the distraction gap is called regenerate. The interval between osteotomy and the start of lengthening is called the latency phase and is usually 7 to 10 days. The correction and lengthening is called the distraction phase. The time from the end of distraction until bony union is called the consolidation phase. Of the phases of the Ilizarov method, the consolidation phase is the most variable and the most affected by patient factors such as age and health. If the structure at risk is a nerve, such as the peroneal nerve in a patient with a proximal tibia valgus deformity or the posterior tibial nerve in a patient with an equinovarus deformity of the ankle, gradual correction may be the safer option. The correction can be planned so that the structure at risk is stretched slowly.[3,4] If nerve symptoms do occur, the correction can be slowed or stopped. Nerve release can be used in selected patients based on the response to gradual correction.[4]

Gradual lengthening after acute correction of deformity can be accomplished with a specialized intramedullary nail that has the capacity for gradual elongation. This process uses the principle of distraction osteogenesis and has the advantage of avoiding external fixation. The principle disadvantage of gradual lengthening is the difficulty with distraction rate control[38] (Figures 7 and 8).

There are hybrid methods that use combinations of internal and external fixation for gradual lengthening and correction. With lengthening over a nail, an intramedullary nail is inserted after the osteotomy with only proximal interlocking screws. A frame is applied with no contact between internal and external fixation. The frame is used for distraction over the nail. Once distraction is complete, the nail is locked distally, and the frame is removed. This method has the principal advantage of substantially reducing the time patients must be in the external fixator because the nail supports the regenerate during the consolidation phase. Additional advantages over traditional lengthening include faster return of knee range of motion and protection against refracture.[39]

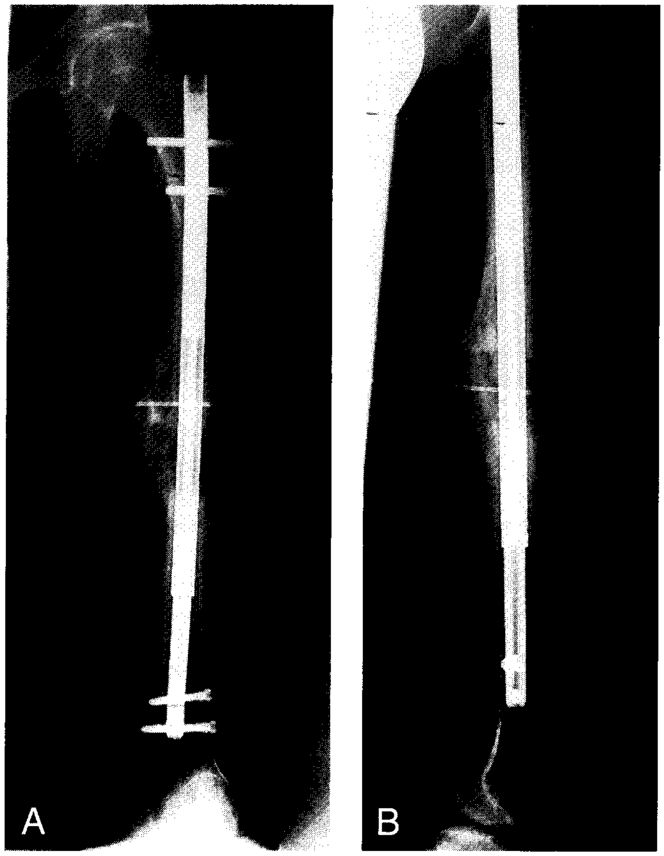


Figure 8 AP **(A)** and lateral **(B)** radiographs of the patient in Figure 7 6 months after surgery show correction of the deformity and lengthening of 4 cm with internal lengthening nail (ISKD, Orthofix, USA) in place.

Another hybrid method is lengthening followed by nailing. A frame is applied with the pins placed so there will be no contact with future intramedullary nailing. The osteotomy is performed and gradual lengthening and correction is performed with distraction osteogenesis. Once distraction is complete, the statically locked intramedullary nail is inserted and the frame is removed. As with lengthening over a nail, the time patients must be in the external fixator is reduced and there is decreased risk of refracture compared with traditional lengthening. In addition, a longer and larger diameter intramedullary nail can be used for a more stable con-

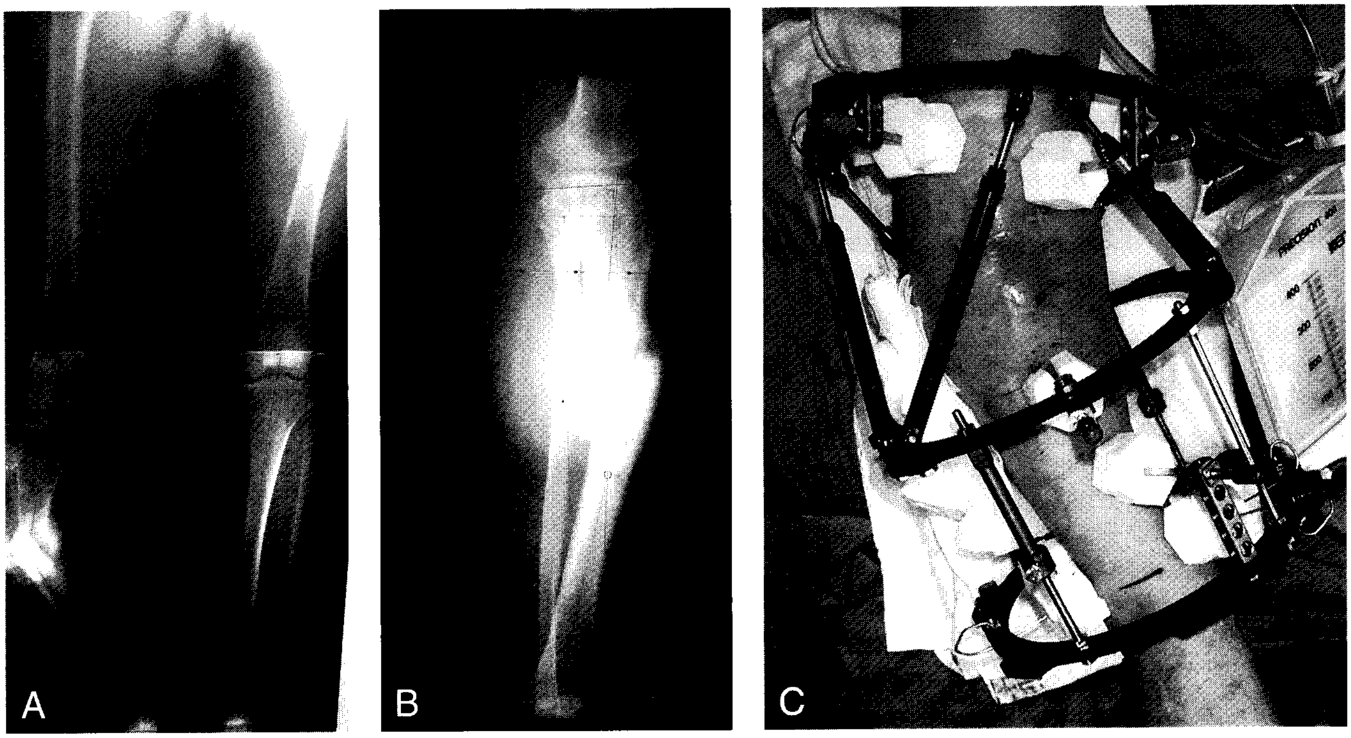


Figure 9 Preoperative AP **(A)** and lateral **(B)** radiographs show a hypertrophic tibia nonunion with deformity and shortening. **C,** Immediate postoperative photograph, frontal view, shows the Ilizarov/Taylor Spatial Frame in place matching the deformity.

struct. Gradual correction of both the deformity and the limb-length discrepancy can be accomplished before the intramedullary nailing procedure. Reaming through the regenerate appears to have a stimulatory effect, and bone healing is rapid.[40] The principal disadvantage of these hybrid methods is the increased risk of deep infection. This risk can be minimized with meticulous technique.

Hypertrophic Nonunion

An excellent application of gradual correction is for patients with a hypertrophic stiff nonunion with deformity. This type of nonunion has fibrocartilage tissue in the nonunion and has the biologic capacity for bony union. It lacks stability and axial alignment. Gradual distraction to achieve normal alignment results in bone formation. The nonunion acts similar to regenerate, and bony healing occurs. Modest lengthening of no more than 1.5 cm should be done through the nonunion. If additional lengthening is needed, a second osteotomy for lengthening is performed. Several studies have confirmed initial success with this technique.[3,5,27,32,37] The principal advantages of using gradual correction to treat patients with a hypertrophic stiff nonunion with deformity are not having to open the nonunion site in patients with poor skin quality and widened callus and gaining length through an opening wedge correction (Figures 9 and 10). This technique is not useful for treating patients with mobile atrophic nonunions and is less applicable to treating those with infected nonunions.

Hypertrophic nonunions can also be treated with internal fixation. Compression plating and intramedullary nailing can be used successfully, especially in patients with a relatively small deformity and healthy soft-tissue envelope.[26] Bone grafting is usually not required in this patient population.

Atrophic and Normotrophic Nonunions

Atrophic nonunions have fibrous tissue at the nonunion site and tend to be mobile. Treatment needs to be directed toward improving both the biology and the mechanical environment to achieve bony union. Normotrophic nonunions have both fibrous and fibrocartilage tissue at the nonunion site and are therefore less mobile than atrophic nonunions. Atrophic and normotrophic nonunions should be exposed, bone ends should be contoured so there is healthy bleeding bone on both sides with good contact, and intramedullary canals should be opened. Stripping of soft tissue should be performed in moderation. Acute correction of deformity should be followed by bone grafting and stable fixation with compression. This can be accomplished with a plate, intramedullary nail, or an external fixation frame depending on surgeon preference and location. Compression plating of aseptic humeral nonunions has been used successfully.[25,26] For diaphyseal nonunions of the humerus,

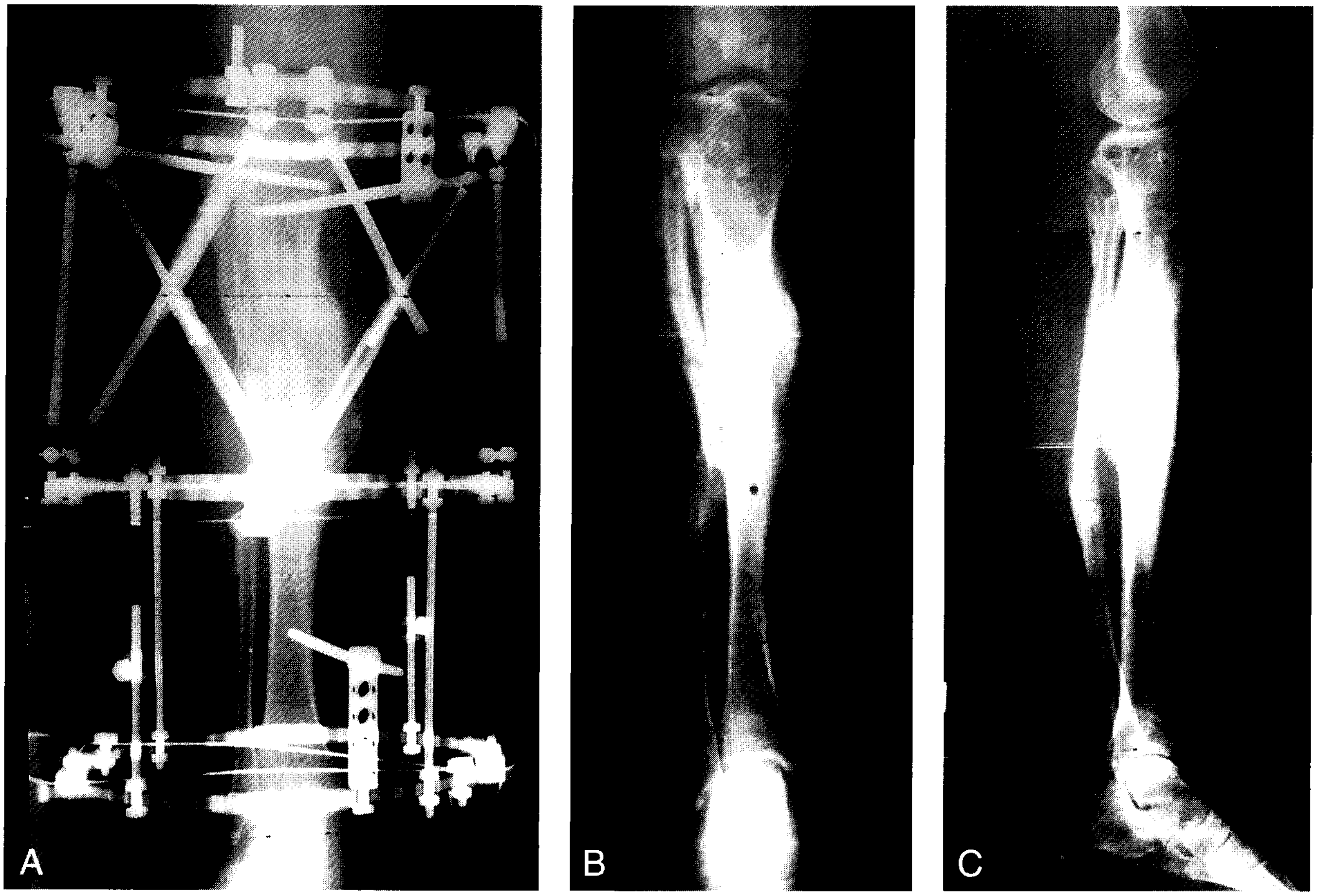


Figure 10 **A,** AP radiograph of the patient in Figure 9 5 weeks after surgical distraction of the nonunion. Note that no osteotomy and no open approach was performed. AP **(B)** and lateral **(C)** radiographs of the same patient 6 months after surgery show bony union and correction of deformity.

a second plate can be used 90° to the first or an allograft strut can be used if adequate stability is not achieved with one plate.[26] In contrast to acute fracture treatment where rigid stability is not the goal,[41] the goal for stabilization of nonunions should be a relatively rigid construct.[3,25,26]

Several studies have supported the use of reamed intramedullary nailing for the treatment of tibial[18,19] and femoral[13-17] nonunions. This is particularly useful in patients who have undergone previous intramedullary nailing and those with no infection or bone loss. Circular external fixation can also be used to treat atrophic and normotrophic nonunions. In patients with atrophic nonunions, the frame is used for stabilization after acute correction and an open approach. An advantage of using a frame is that in addition to the ability to acutely compress the nonunion in surgery, more compression can be added during the postoperative period. The frame is also stable enough to allow full weight bearing right after surgery.[28,30] Another method for treating recalcitrant normotrophic nonunions after intramedullary nailing in patients without deformity is augmentative Ilizarov frame fixation.[29] This allows intramedullary nail retention, and additional compression and stabilization is accomplished with the frame.

Normotrophic nonunions can also be treated with gradual correction. The nonunion can be approached in a minimally invasive fashion using 1- to 2-cm incisions. With the aid of intraoperative fluoroscopy, the nonunion can be mobilized with an osteotome, and the intramedullary canals can be opened by using a cannulated drill and curets. Bone graft can then be inserted. The frame is then applied and used to gradually correct the deformity (angulation and translation). Once this is accomplished, axial compression is then performed. Full weight bearing is allowed immediately after surgery. If additional length is needed, an osteotomy for gradual lengthening can be performed at a different site. Lengthening and then nailing techniques can be used in these patients. This provides autogenous bone graft from reaming and protects against refracture.

Nonunions after tibial pilon fractures can result in metaphyseal nonunion combined with ankle arthrosis. Infection, poor soft-tissue quality, and retained hardware often complicate these injuries. Treatment should be directed toward repair of the distal tibia, correction of the deformity, and ankle arthrodesis if necessary. This can be accomplished with internal[22] or external fixation. If bone resection is needed as in the case of infection, then ankle fusion and simultaneous tibial lengthening can be done with the Ilizarov method.[42]

Infection

Infected nonunions are complex injuries that are challenging to treat. Typically, infected nonunions are atrophic and mobile. They can also be stiff and hypertrophic. Infected nonunions are typically approached in an open fashion. The goals of surgery are to remove all dead bone, open the intramedullary canals, appose bleeding bone surfaces, and correct the deformity. The patient should ideally have not been receiving antibiotics for several weeks, and multiple intraoperative cultures and pathology specimens should be sent to the laboratory at the time of surgery. The nonunion is then mechanically stabilized. With the help of an infectious disease consultant, treatment of chronic osteomyelitis is rendered. This usually consists of culture-specific intravenous antibiotics for 6 weeks followed by an oral regimen. Removal of dead bone is needed to eradicate infection. Bone graft should not be used during the primary surgery. Antibiotic beads can be used for dead space management and local antibiotic delivery. Several weeks later, the antibiotic beads can be removed, and the nonunion can be bone grafted. The use of absorbable antibiotic beads made of calcium sulfate has been advocated by some to avoid the need for antibiotic bead removal and subsequent bone grafting.[43] Problems with persistent drainage have been reported using this technique.[43]

Stabilization can be accomplished with a plate, intramedullary rod, or an external frame. The plate and intramedullary rod have the disadvantage of adding foreign material to the infected site.[44] They can, however, be used with caution in patients with a nonpurulent infection of the femur or humerus. The use of internal fixation to treat an infected tibial nonunion or in any purulent infection primarily is fraught with risk. The use of a frame is the preferred approach in most patients with infection. It has the advantage of not adding foreign material to the infection site and can be used to treat more complex situations. If débridement of the nonunion results in a bone defect, the frame can be used for bone transport or acute shortening and gradual lengthening[3,30,31] (Figure 11).

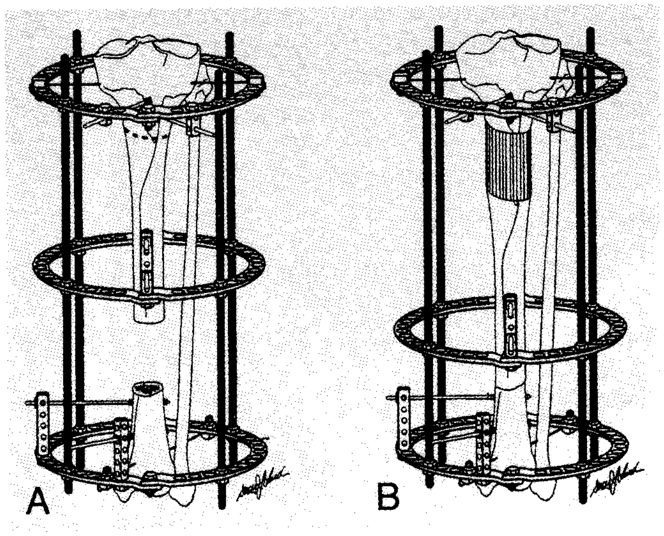


Figure 11 **A,** Illustration of bone transport used to treat a tibial bone defect. **B,** A proximal tibia osteotomy is shown. *(Reproduced with permission from Paley D:* Principles of Deformity Correction. *Berlin, Germany, Springer-Verlag, 2002.)*

Staging Treatment

Staging the treatment is an important strategy for nonunion management. In patients with infection, antibiotic beads may be removed after several weeks and bone graft inserted. In the patients in whom bone débridement resulted in a bone defect, gradual or acute shortening with a frame may be used. An osteotomy for lengthening can be done several weeks later, after the infection is cleared and after the patient and surgeon have decided on whether to perform limb lengthening or use a shoe lift. This has the advantage of protecting the osteotomy site from contamination. In addition, it is often difficult to predict the precise amount of bone resection needed. Once this is known, the patient and surgeon can make a more informed decision about limb lengthening.

When bone transport is used to treat a bone defect, the docking site should be prepared when there is a gap of approximately 1 cm. Preparation of the docking site includes débridement of fibrous tissue, realignment of bone ends to maximize bony contact and minimize deformity, and the addition of bone graft. This improves the rate of bony union.[31]

If the soft-tissue coverage is poor, flap coverage may be needed. A staged approach with a plastic surgeon can be helpful. For example, bone and soft tissue may be débrided and a simple frame applied that allows the plastic surgeon access to the wound. After flap coverage has been accomplished, bone transport can be done to treat a bone defect, or the flap can be elevated after several weeks and the nonunion site bone grafted.

Indications for Amputation

Attempts have been made to help determine indications for lower extremity amputation after acute trauma to avoid futile attempts at limb salvage. The indications for amputation after nonunion are complex and ever changing. There is a significant psychologic aspect to this; some patients believe that they have invested so much in saving the limb that they want to keep trying. Others have been worn out by the effort and are ready to move on after amputation. Some patients are not willing to have an amputation even if it is clear that it will improve functional outcome. When possible, below-knee instead of above-knee amputation should be done.

Indications for amputation have changed with the improved ability to reconstruct compromised limbs. Infection, bone loss, deformity, limb-length discrepancy, and poor soft-tissue coverage are no longer absolute indications for amputation. (If these indications were combined with an insensate foot and chronic neuropathic pain, it would be an indication for amputation.) The indications change with the ability of orthopaedic surgeons to successfully reconstruct the nonunion. Nevertheless, the factors that are most problematic are chronic neuropathic pain, lack of sensation on the plantar surface of the foot, and a stiff foot and ankle. The best treatment option for such patients is best determined by assessing all of the features of the nonunion and taking the needs of the individual patient into account.

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The purpose of this retrospective study was to analyze the results of treatment of nonunions of the distal part of the femur with internal fixation combined with cortical allograft struts and autogenous bone grafting. The authors reported that open reduction and internal fixation supplemented with allograft struts and autogenous bone graft was an effective treatment of nonunion of the distal part of the femur.

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Hypertrophic nonunions with deformity are an unusual complication after Coventry-type high tibial osteotomy. The authors found that these can be treated successfully by gradually distracting the nonunion without an open approach, which results in bony healing, correction of deformity, and increased metaphyseal bone stock; this technique should be helpful if total knee replacement were to become necessary in the future.

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Rates for complications, such as nonunion and osteonecrosis, after femoral neck fractures in young patients have been reported to be as high as 86%. Treatments such as osteotomy, muscle-pedicle bone grafting, nonvascularized bone grafting, and vascularized bone grafting have been reported to have variable results. Based on the results reported in this study, vascularized fibular bone grafting compares favorably with a high union rate (91% initially, 100% after secondary procedures), and successful long-term salvage of the femoral head was achieved in 91% of the patients. The authors concluded that free vascularized fibular bone grafting represents a promising solution for this difficult problem.

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This was a review of 41 femora in 31 patients who underwent femoral lengthening with a fully implantable lengthening device. One third of the patients had posttraumatic limb-length discrepancy. The intramedullary nail was inserted antegrade after a femoral osteotomy. The mean gain in length was 3.4 cm (range, 2.0 to 5.5 cm) in the unilateral patients.

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In this study to assess the use of bioabsorbable, tobramycin-impregnated bone graft substitute in the treatment of 25 patients with infected bony defects and nonunions, the authors found that the bone graft substitute was effective in eradicating bone infection in 23 of the patients.

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In this study, 10 infected humeral nonunions were treated surgically with external fixation, plating, tension band wiring, and bone grafting. All were débrided and treated with intravenous antibiotics. Bony union was achieved in 7 of 10 patients. The authors concluded that infected humeral nonunions are much more difficult to treat than aseptic nonunions and that additional data are required to determine the best treatment method.