41 Management of Aseptic Malunions and Nonunions

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Learning Objectives/Questions Covered
- Describe evaluation of the patient with disordered bone healing.
- Discuss diagnosis of nonunion.
- Explain classification of nonunion.
- Enumerate non-operative treatments for nonunion.
- Identify surgical goals and steps.
- Elaborate upon the source and use of bone graft and substitutes.
- Remind the reader about the use of implantable bone stimulators.

41.1 Introduction

Disorders of skeletal healing after fracture take the form of malunion, nonunion and delayed union. Malunion is defined as healing of the bone in an abnormal shape that results in a clinically significant alteration in function. For diaphyseal locations, this can take the form of angulation, shortening, or rotation that alters the relationship of joints to each other and impairs the function of the limb. Nonunion refers to the situation in which bone healing has ceased without restoring the structural integrity of the bone. Practically, this is usually diagnosed after some period of time has passed, usually 3 months, without radiographic or clinical improvement, although in some cases of significant bone loss (designated *a critical defect*) healing is so unlikely that it could be considered an instant nonunion. The term delayed union refers to the situation in which the bony healing process is incomplete beyond the time which would be expected but is believed to be still active; or in which there is no radiographic or clinical progress, but it is still too soon to declare that it will not occur. This is a subjective assessment.

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41.2 Patient Evaluation and Diagnosis

Patients with both malunion and nonunion may present with complaints of pain and/or deformity. As with any patient, a thorough history and physical exam should be performed. It is assumed that the readers of this chapter are familiar with that process, and so just a few of the relevant findings will be mentioned here as a reminder. Significant historical information includes details of the injury (open vs. closed; associated vascular or neurologic damage; other injuries; prior treatments, timing, outcomes; any history of signs, symptoms, or treatment of infection), as well as information about the patient (age and occupation; medical illnesses and medications; habits;

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compliance with previous treatments; social support situation; and psychological resilience). The treatment of these problems is complex and prolonged, so it is very useful at the outset to get to know the patients and their lives in order to help set realistic goals. A detailed history of the complaints and impairments takes time but is very useful in understanding what they hope to achieve by treatment and in managing expectations. It is rarely possible to make people "good as new" once they have developed a skeletal healing disorder, and that should be stated early in the process.

The physical examination, as always, should be thorough, which means that the patient should be adequately disrobed in order to examine the entire limb as well as the contralateral side. The location and status of previous scars should be noted, or even drawn in the chart, with an eye to vascularity of the soft tissues, skin changes suggestive of chronic infection, and possible location of surgical exposures needed. Do not forget palpation for tenderness, fluctuance, and soft tissue mobility. Deformities should be noted and quantified, particularly rotational variations from the contralateral side. Range of motion of adjacent joints, strength and size of musculature, motor and sensory function should be documented. Observe the function of the limb by having the patient walk in the hallway or perform functional activities with the upper extremity.

Radiographs should include the entire bone, with good orthogonal imaging of the joint above and below the fracture. In the case of malunion, contralateral films will usually be necessary. For the lower extremity, standing films of hip, knee, and ankle bilaterally are usually required to fully characterize the mechanical effects of the deformity; although occasionally a simple malunion will be confined to a single bone and that will be obvious. There is variation between people in the normal alignment and the goal should be to correct the person to a symmetrical alignment unless there is concomitant pre-existing abnormality, in which case correction of a malunion may be part of a comprehensive skeletal re-alignment process. Those are complex situations which should be referred to an experienced team. CT scans are helpful in delineating and locating rotational deformities that are identified on clinical examination. For the lower extremity, cuts through the femoral neck, distal femur, and distal tibia are usually obtained to compare rotational alignment to the unaffected side.

Laboratory evaluation will be guided by the patient's medical history. In almost all cases, any evidence of infection should be sought through assessment of the white blood cell count (WBC), C-reactive protein level (CRP), and erythrocyte sedimentation rate (ESR). ESR and CRP have been shown to be independently accurate predictors of infection; in one study of nonunion, if all three indices are elevated, 100% of patients turned out to be infected [1]. Most orthopedic trauma surgeons are aware of the high incidence of metabolic disorder or endocrinopathy in patients with unexpected nonunion. A high percentage (>80%) of patients with nonunion of low energy or nondisplaced fractures have been found to have endocrine abnormalities, most commonly vitamin D deficiency (~70%), but also abnormalities of calcium, thyroid or parathyroid function, diabetes, growth hormone, and hypogonadism [2]. Work-up includes a comprehensive endocrine and metabolic profile with serum and urine testing for abnormalities in a defined set of vitamins, minerals, and hormones [3].

41.3 Classification of Nonunion

Nonunions can be classified, primarily on the basis of radiographic appearance, and that classification may help guide treatment. The categories are: infected, atrophic, hypertrophic, oligotrophic, segmental bone loss, and synovial. Infected nonunions are not the focus of this chapter, but the presence of infection may not be known until the time of surgery or after, and so the possibility must always be kept in mind and discussed with the patient at each stage. A patient with an infected nonunion has two interrelated problems, nonunion and osteomyelitis, and both conditions require a treatment strategy. In many cases these coordinated plans will require staged surgical procedures with specific goals and timing. In patients with a “hot” infection (pain, erythema, purulent drainage, systemic symptoms), treatment may be initially directed at acutely controlling the infection, followed by attempts to achieve union. If the infection is more indolent, bony union may be the first goal. It is difficult to achieve long-term infection control if there is bony instability. Functioning, stable hardware rarely needs to be removed until union has been achieved, even in the face of infection, because instability is worse than the presence of foreign material, in terms of prolonging the infection. Ultimately, after bony healing is achieved, hardware may need to be removed for long-term definitive infection control.

The terms atrophic, hypertrophic, and oligotrophic refer to the radiographic appearance of reactive bone or callus at the fracture site. In atrophic nonunion, there is very little or no callus formation, and the ends of the bone are often tapered and wispy; they have been described as looking like the end of a sharpened pencil. Hypertrophic nonunions have an abundance of callus built up at the nonunion site, often on both sides, but not bridging across the fracture line. They have been described as having the shape of an elephant’s foot. Oligotrophic nonunion is a rather vague and subjective category that falls in between the other two. The basic idea of this classification is the observation that hypertrophic nonunions usually heal easily when they are rigidly stabilized with internal fixation, while atrophic nonunions are felt to need some sort of additional biologic stimulation such as bone grafting in addition to rigid stabilization. While some have speculated that the difference between atrophic and hypertrophic nonunion results from a difference in vascularity, a histologic examination revealed that, on a microscopic level, atrophic nonunions are not avascular. Tissue sampled from human nonunions showed no difference in the blood vessel density between different types of nonunion [4]. In an animal model of atrophic nonunion, the number of blood vessels reached the same as in normal healing bone, but at a delayed time point, suggesting that avascularity in the first weeks of fracture healing may play a role in development of atrophic nonunion [5]. Anecdotally, atrophic nonunions do tend to occur in situations in which there is a less robust soft tissue envelope, such as open tibia fractures or cachectic patients.

There are additional concerns when there is a situation of segmental bone loss in the face of nonunion. In some situations, with short defects or in the upper extremity, shortening of the limb segment may be acceptable. The methods of reconstructing segmental defects include cancellous bone grafting, bone transport, and vascularized tissue transfer. Vascularized tissue transfer requires experience and expertise in microvascular techniques. Bone transport will be discussed in another chapter. Cancellous bone grafting indications, techniques, and outcomes will be discussed later in the chapter.

Synovial nonunions (true pseudo-arthrosis) are those which have developed a sterile fluid-filled, membrane-bound cavity between the ends of the bone, which often are covered with fibrocartilage, very similar to an actual synovial joint. Treatment of this type of nonunion is similar to an arthrodesis procedure, with debridement, apposition of bleeding bone, compression, and internal fixation.

41.4 Diagnosis of Nonunion

The diagnosis of nonunion is both clinical and radiographic. Although some nonunions are asymptomatic (e.g., clavicle), many cause symptoms of pain or instability. On physical examination, there may be tenderness or pain on manual stress. There may be gross instability of the bone and the appearance of an additional joint (hence the term “pseudo-arthrosis”), and this finding is more common in atrophic nonunion or cases of bone gap. In those cases, the diagnosis is not subtle or difficult. Examination using manual stress radiographs or fluoroscopy can document gross instability. The more controversial situation occurs in the hypertrophic (stiff) nonunion, or when there is internal fixation in place which both masks instability and obscures radiographic detail. Pain on weight-bearing has been considered a sign of nonunion, but can be multifactorial. Some well-united fractures can have pain related to activity. A common definition of radiographic union is bony bridging of 3 out of 4 cortices of the diaphysis. This common usage definition was formalized into the Radiographic Union Scale for Tibia fractures (RUST) score by Whelan and coauthors [6]. The score is produced by using AP and lateral views of the tibia showing the fracture site and scoring each of the four cortices at the fracture site (anterior, posterior, medial, and lateral) on a scale of 1 to 3. A score of 1 means there is no bridging callus and the fracture line is visible, a score of 2 means there is bridging callus but the fracture line is still visible, and a score of 3 means there is bridging callus and the fracture line is not visible. The scores are then summed. Although there is no score that defines union, this has been determined in subsequent studies. This score has been shown to have a high interclass correlation coefficient (ICC) when used for diaphyseal fractures treated with intramedullary nailing [7] and moderate agreement for meta-diaphyseal fractures of the distal femur and proximal tibia [8]. The RUST score was modified in 2015 by Litrenta and colleagues with a slight improvement in ICC (6.8 vs. 6.3) [8]. Observers in that study assigned an average RUST score of 8.5 to fractures they considered united, while the average *modified* RUST for fractures considered united was 11.4.

Most textbooks suggest that if a healthy patient has pain, lack of three bridged cortices at 9 months and is showing no progressive improvement on radiographs over 12 consecutive weeks, they may be considered non-united. This definition has been adopted by the FDA [9] and by many insurance companies to evaluate payment for nonunion treatments, particularly bone stimulators. Some surgeons have a more aggressive approach to intervening earlier if they see no progress to healing. However, recent evidence suggests that, at least for tibia fractures, a significant portion of fractures that are judged non-united at 3 months will go on to heal by 6 months, and caution is warranted prior to rushing to additional treatment [10]. Of course, some fractures are "instant nonunions" due to bone loss that exceeds a critical healing defect size.

CT scan is more accurate than plain radiography in diagnosing tibial nonunion. Several studies have shown a sensitivity of 100%, but lower specificity (~40–80%). The cost and radiation doses involved have limited the routine use of CT scans to evaluate healing of most fractures [11, 12]. Ultrasound has been used to evaluate healing of tibia fractures at an early stage with some promising results, particularly in terms of prediction of ultimate healing; however, it is felt to be highly operator dependent and is not in wide clinical use [11]. Current research involves evaluation of serologic and formal biomechanical methods to evaluate union, but for now, physical exam and plain radiographs form the mainstay of diagnosis for bone union.

41.5 Treatment of Nonunion

Treatment should always begin with a search for, and addressing, any correctible host healing factors. Metabolic and endocrine disorders have been mentioned and should be treated as necessary with optimization of diabetic control, renal function, vitamin D supplementation, and replacement of hormonal deficiencies. Peripheral vascular disease can be diffuse or focal, can contribute to the development of nonunion, and should be sought by history and physical examination. In appropriate patients, a formal vascular work-up may be indicated to identify correctable obstructions prior to any significant limb surgery. Certain medications have been shown to inhibit fracture healing, and they should be avoided when possible. Animal and cell culture studies suggest that certain antibiotics (fluoroquinolones, aminoglycosides, rifampin) may have negative effects on bone cell biology and fracture healing. Likewise, animal studies have demonstrated than anticoagulants (heparin and warfarin) significantly attenuated the process of fracture healing, but no human studies have shown this [13]. By far the most common and controversial issue revolves around non-steroidal anti-inflammatory drugs (NSAIDs). These drugs have been shown to inhibit fracture healing in cell culture, multiple animal species, and many human studies [14–16]. However, the dosage, timing, and specific at-risk populations are not known with clarity. Due to the current opioid medication crisis, NSAIDs are promoted as a safer method of pain control following fracture, and proponents minimize the risk of nonunion or delayed union. It should be noted that there are no good studies demonstrating that addition of NSAIDs to pain medication protocols actually reduce the incidence of addiction and overdose although they can reduce the amount of narcotic medication used by patients. Many authors believe that the available literature does not prove that a short course of NSAID treatment will increase risk of bone healing problems in a normal healthy host, particularly a younger person. However, it seems prudent to avoid these medications in a patient with other risk factors for impaired bone healing. Dietary strategies for healing include vitamin and mineral supplementation, and addition of protein with conditionally essential amino acids [17, 18]. The addition of micronutrients important in the production of collagen (vitamin C, vitamin B6, proline, lysine) has been shown to speed tibial fracture healing in accelerate tibial fracture healing in a prospective, randomized, double blind, placebo-controlled trial [19]. Attempts should be made to address nicotine addiction, or other habits which may be detrimental. One should encourage the patient to see themselves as a partner in the healing process, and to take some responsibility for getting the bone united. There is undoubtably a psychological component to successful treatments of any injury and evidence of impairment in the psychosocial realm should lead to evaluation and treatment of depression, anxiety, or post-traumatic stress disorder. It is emphasized that the treatment on nonunion is often a long and difficult undertaking, in which surgery is only a small part, and the patient should be in the best possible state physically, mentally, and spiritually before undergoing the surgical portion. In some cases, particularly after a course of previous treatments that have failed, discussion of amputation as a reconstructive procedure may be in order.

41.6 Non-operative Treatment of Nonunion

Non-surgical treatments for nonunion include bone stimulators, functional bracing, systemic medications, and injections of platelet-rich plasma (PRP), mesenchymal stem cells, or bone marrow aspirate. Bone stimulators provide a physical signal to the bone that has a biologic effect. The signal can be electromagnetic in nature, or ultrasonic. The biologic effects of electromagnetic stimulation have been known for decades and include increased production of bone morphogenic protein 2, alkaline phosphatase, cytosolic calcium, and activated cytoskeletal calmodulin [20]. All electromagnetic stimulators function by production of a small electric current in the bone, but they do it by different mechanisms. The direct current stimulators are implanted surgically and apply the cathode and anode of a battery directly to tissues. This creates a current and induces chemical changes in the bone at the cathode wire that create conditions that promote differentiation of stem cells into bone. Noninvasive stimulators are of basically two types. Inductive coupling stimulators produce a current by creating a time-varying magnetic field which induces current flow in the conducting tissue. The electromagnetic field can be pulsed, sinusoidal, or combined static and sinusoidal. Capacitive coupling systems function by creating an electrical field with a voltage gradient between two charged plates, which in turn produces a current flow. The ultrasonic stimulator creates a mechanical signal using ultrasound, similar to but stronger than the sound waves used for diagnostic ultrasound. There is a large amount of literature on the effects of both electromagnetic stimulation and ultrasound stimulation on bone healing, including basic science, animal studies, and clinical studies [21]. Meta-analyses of this literature were performed in the early 2000s and resulted in differing conclusions. Three of them suggested a positive effect, and one did not [22–25]. A more recent meta-analysis of randomized, sham-controlled studies found moderate quality evidence from 15 studies that bone stimulation reduced radiographic nonunion rates and reduced pain [26]. The use of a bone stimulator is relatively contraindicated in nonunions with a synovial cavity, with a bone gap greater than half the diameter of the bone, or with unacceptable malalignment. They seem to work better with hypertrophic nonunions, and in bones that are closer to the skin surface.

Functional bracing has been used to treat nonunions of the tibia. Sarmiento and coauthors treated 73 patients with tibial nonunion or delayed union with functional bracing, and followed 67 of them until outcome was determined. The nonunions were in the brace for an average of 4 months; six patients in the series failed to heal, five of which were in patients who had suffered open fractures. All of the patients had deformities that were considered "aesthetically acceptable" in the opinion of the authors, and 48 patients had fibular ostectomy (1 cm of bone removed at least 2 cm above or below the lesion), which was used when motion at the fracture site was more than "minimal." Bone grafting was performed in 10 patients who had a history of multiple failed previous surgical procedures. Weightbearing in the functional brace was an essential part of the treatment success [27].

Systemic administration of Teriparatide (human parathyroid hormone, N-terminal amino acids 1–34), given by weekly subcutaneous injection, has been used successfully to heal nonunion in case reports [28, 29]. Percutaneous injection of bone marrow aspirate at the nonunion site was first reported by Connolly in 1986, and since that time there have been many reports of the use of this technique with success rates varying from 75% to >90% [30–35]. Although most of the studies are small, retrospective series without control groups or blinded reviewers [33–35], the technique has low risk, and burns no bridges for later procedures. It is most useful in cases of aseptic NU or DU following internal fixation, where the hardware is stable and functional. Bone marrow aspirate injection has been combined with low-intensity ultrasound for treatment of recalcitrant long bone nonunion in one series, with 76% success after a year [36]. Bone marrow aspirate may be centrifuged to concentrate the nucleated cell fraction and increase the concentration of osteoprogenitor cells [32]. This may be combined with commercially available osteoconductive scaffolds to provide an optimal combination graft substitute [3].

Platelet-rich plasma (PRP) created by intraoperative processing of autologous blood has been used to stimulate healing in NU and DU, with reports being primarily small retrospective case series without control groups or blinded evaluation. Some studies have shown a promising effect [37, 38], while others have not [39].

41.7 Surgical Treatment of Aseptic Nonunion

When non-operative treatments have failed or are unlikely to succeed, the patient may choose surgical treatment. The goals of surgery are to provide increased stability in the correct alignment and to restart the healing process in a more favorable biologic and mechanical environment. The specific steps of the surgical treatment will depend upon the type of nonunion, the presence of deformity, and the details of previous treatments (Table 41.1). The simplest situation is an aseptic hypertrophic nonunion with acceptable alignment. In this case, the addition of mechanical stability alone, using internal fixation techniques (intramedullary nails or extramedullary plates), will lead to success in a high percentage of cases. The nonunion site does not need to be debrided or resected, because in the correct mechanical milieu, the scar and cartilage tissue will ossify. "Takedown" (debridement) of a nonunion is necessary only when there is excessive deformity, a true synovial pseudarthrosis, or an infected nonunion. If there is deformity that is outside acceptable ranges, correction of alignment usually occurs simultaneously to internal fixation and may involve surgical debridement or osteotomy through the nonunion site. In the atrophic or oligotrophic nonunion, some sort of biologic stimulation, such as bone grafting is required in addition to correction of alignment and provision of stability. The nonunion with bone loss will require stability, correction of alignment, biologic stimulation, and restoration

Table 41.1 Surgical requirements for nonunion types

Nonunion type	Enhance stability	Biologic stimulation	Debridement	Restore bony structure	Antibiotics
Hypertrophic	✓				
Atrophic	✓	✓			
Synovial	✓	✓	✓	±	
Bone loss	✓	✓	✓	✓	
Infected	✓	✓	✓	±	✓

All nonunions with unacceptable deformity will require correction of alignment

of structural integrity. A synovial nonunion will require increased stability, correction of alignment, and debridement of the synovial cavity. After that debridement, some cases will be improved with biologic stimulation and/or additional restoration of bony structure. Finally, the infected nonunion will need stability, correction of alignment, debridement, and antibiotics. Depending upon the extent of debridement, some of them may need grafting to restore structure to the bone.

The common basis for surgical treatment of each type of nonunion is restoration or enhancement of mechanical stability, and this is the role of internal fixation. Previous treatment may have resulted in inadequate stability from gaps or malreductions, or through failed fixation constructs. Analysis of mistakes that may have been made in previous treatments is essential and can guide the subsequent procedure. Common situations include plates that are too short, too thin, or improperly positioned or applied; screws that are too few, too many, or poorly placed; or intramedullary rods that are too short, too thin, or inadequately locked. These failed implant constructs must be removed, and appropriate fixation applied.

Removal of hardware can be challenging and the surgeon must be prepared for unusual or unfamiliar screw heads or nail extraction requirements. Identification of implants prior to surgery is ideal, in order to plan for having the correct extraction tools. In any event, sets for removal of broken screws should be available and the surgeon should be familiar with their use. Expect stripped threads and heads. In the case of intramedullary nails, long hooks are available and useful for removal of cannulated nails or nail fragments. The bone proximal to the nail or nail fragment should be over-reamed by 1–2 mm to facilitate extraction. If hooks are not available, one can sometimes use two ball tipped reaming rods to extract cannulated nails. The first reaming rod is inserted and advanced until the ball or bead is past the end of the nail. A second rod is inserted with the non-ball tip end leading, and this is advanced all the way to the end of the nail with light blows of the mallet. This forces the ball tip on the first rod into an eccentric position beyond the end of the nail and allows it to function as an extraction hook (Fig. 41.1).

Removed hardware should be cultured to evaluate for possible infection. Intraoperative Gram stain has a high specificity but a very low sensitivity for infection. Unfortunately, traditional culture-based methods for identification of infection may also be ineffective for implant-related infections caused by organisms producing a protective biofilm. Molecular diagnostic techniques are more sensitive than traditional techniques, but the role of these methods in medical microbiology has yet to be defined [40]. Sonication of explanted hardware using low frequency ultrasound increases the recovery of bacteria; however, the presence of microbes does not always indicate a clinically significant infection and does not necessarily warrant treatment. When hardware is removed with no clinical sign or symptom of infections, culture techniques show an unexpected rate of positive results [41].

In general, improvement of stability requires plates and nails that are longer and stiffer, and more firmly attached to bone, than those removed; and more than is often required for acute fracture. Compression of bone ends and fracture fragments should be achieved through plating and lag

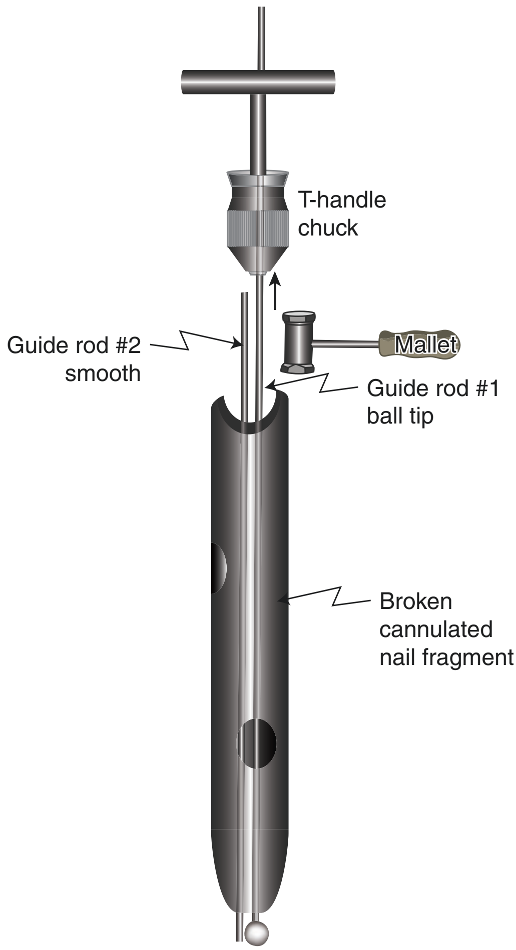

Fig. 41.1 Diagram of the two guide rod technique for removal of a cannulated intramedullary nail when the nail is broken or the threads are stripped. The second, smooth guide rod forces the ball tip of the first rod to an eccentric location, where it functions as a hook on the end of the nail

screw technique whenever possible. Correct anatomic and mechanical alignment is important to allow the forces of muscle contraction and weightbearing to further compress and stabilize the nonunion. Figures 41.2, 41.3 and 41.4 illustrate these principles for the humerus, tibia, and femoral neck.

Dynamization of a nail construct by removing interlock screws and encouraging WB is occasionally successful (~50% of the time in femoral nonunion), but it likely is just a delaying tactic and does come with some risk—primarily shortening in fractures which are not axially stable [42]. In addition, it philosophically plays against the strategy of increasing stability. The same criticism is true regarding fibular osteotomy for tibial nonunion, another treatment of limited reliability when used by itself.

While it has been said that a failed nail should be treated with a plate, and a failed plate with a nail, that is an overly simplistic approach. The point is to do something different and better with the second operation rather than making the same errors again. Certain nonunion locations, such as the diaphysis of lower extremity long bones, lend themselves more easily to enhanced stability through intramedullary nail fixation, even if a previous nailing has failed. When performing an exchange nailing (removing an intramedullary rod used for initial fixation and placing a new one), it is important to identify and correct the deficiencies of the original nailing, by eliminating gaps, correcting alignments, using larger, stiffer implants (1–2 mm increase in diameter, thicker wall) and improving the interlocking. Success rates after femoral exchange nailing for nonunion have varied from 53% to 97%. It is more likely to be successful if clear deficiencies in the original nailing can be identified—excessive gaps, failure to interlock, unreamed, or undersized nails; and it is less likely to be successful in smokers [42]. In the tibia, exchange nailing is successful in a high percentage of aseptic tibial diaphyseal nonunions [43]. A recent report revealed a 97% success rate. Over half the patients (59%) underwent fibular osteotomy and 86% had dynamic compression used. An open surgical approach was used in 17%; when that was necessary, the authors utilized bone grafting and recombinant human bone morphogenetic protein rhBMP-7 [44]. A separate study with a significantly lower success rate (63%) found that presence of infection was a major risk factor for failure of exchange nailing, along with NU atrophic type or residual gap greater than 5 mm [45]. Exchange nailing is generally not successful for nonunions of the humerus.

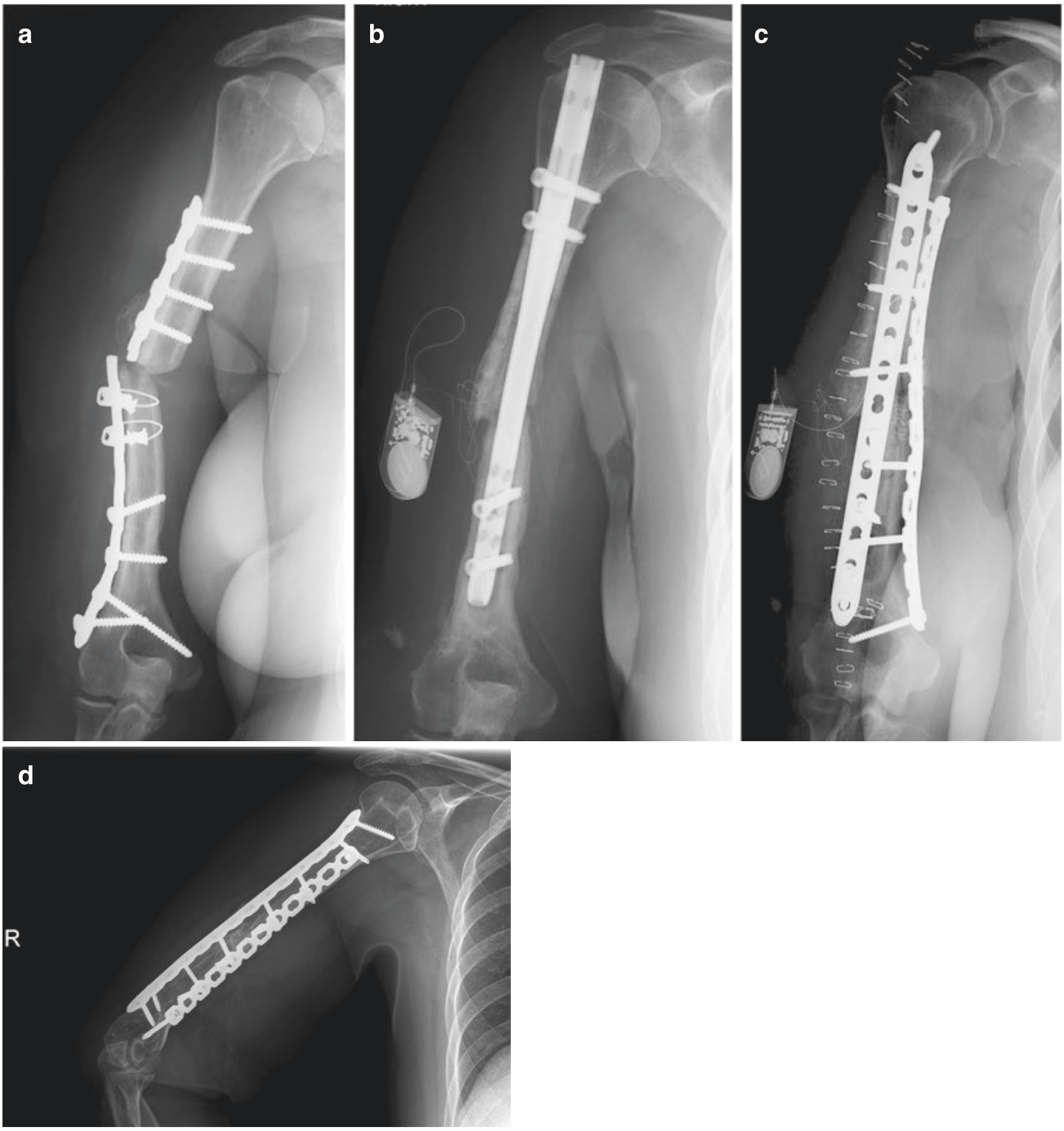

Fig. 41.2 Nonunion of the Humerus. A 45-year-old female patient suffered an isolated midshaft humerus fracture in a fall, which was treated with plating. (**a**) Nonunion developed, possibly due to excessive soft tissue stripping (cables) and plating without compression; and eventually the plate broke. (**b**) The plate was removed and an intramedullary nail placed with bone stimulator. Unfortunately, the oversized nail was locked with a gap at the fracture site, and the nonunion persisted. Prominence of the nail proximally inhibited use of the arm. (**c**) Revision was performed with long 90-90 dual plating, closure of the gap, bone grafting, and repeat bone stimulation. (**d**) The fracture healed with the improved biomechanical environment. (**e**) A 45-year-old obese man had a distal humerus fracture in a motor vehicle accident. It was treated with olecranon osteotomy and Steinman pinning; atrophic nonunion was the predictable result. (**f**) Bicolumnar plating with bone graft led to predictable healing. (**g**) Another example of inadequate plating of the humerus: the plates are too short, and there is a gap at the fracture site. (**h**) Reliable healing following balanced, long, bicolumnar plating, bone grafting, and bone stimulator

Fig. 41.2 (continued)

Some locations, such as upper extremity and peri-articular nonunions, are better treated with plates. The length of plate necessary in treatment of nonunion is dependent upon the specific bone, location of the fracture, effects of previous hardware, and quality of the bone. Commonly repeated rules about the number of "cortices" of fixation required for plate stabilization of a particular bone are not evidence based, and biomechanical testing has shown that the length of the plate is more important to stability than the number of screw cortices used to attach it to the bone. When in doubt, go longer; but you do not need to fill every hole, particularly in good quality bone. Each screw hole in a plate is an opportunity, not an obligation. The use of locking plate technology is useful in obtaining stable fixation in osteoporotic bone, but always be careful not to compromise on fracture compression or the use of lag screw technique in favor of locking. Compress first, then lock if necessary.

Fig. 41.3 Nonunion of the Tibia. (**a**) A 42-year-old painter fell from a scaffold and suffered an open, segmental tibial fracture. (**b**) Treatment consisted of wound care and eventually, dual plating; however at 2 years after injury, he continued to have pain and inability to WB due to his 2 level atrophic nonunion. (**c**) Treatment consisted of hardware removal, creation of a tibial intramedullary canal, reamed interlocked nailing, bone graft, and bone stimulator. (**d**) By 5 months, he was FWB and had returned to work on a healed tibia. (**e**) This tibial nonunion in a 33-year-old rodeo clown, was treated with open cerclage and unreamed nailing. His atrophic nonunion was not solved by removing the distal interlocks. (**f**) The ultimate solution involved improving the stability with a larger, reamed, solidly interlocked nail, with posterolateral bone grafting and bone stimulator

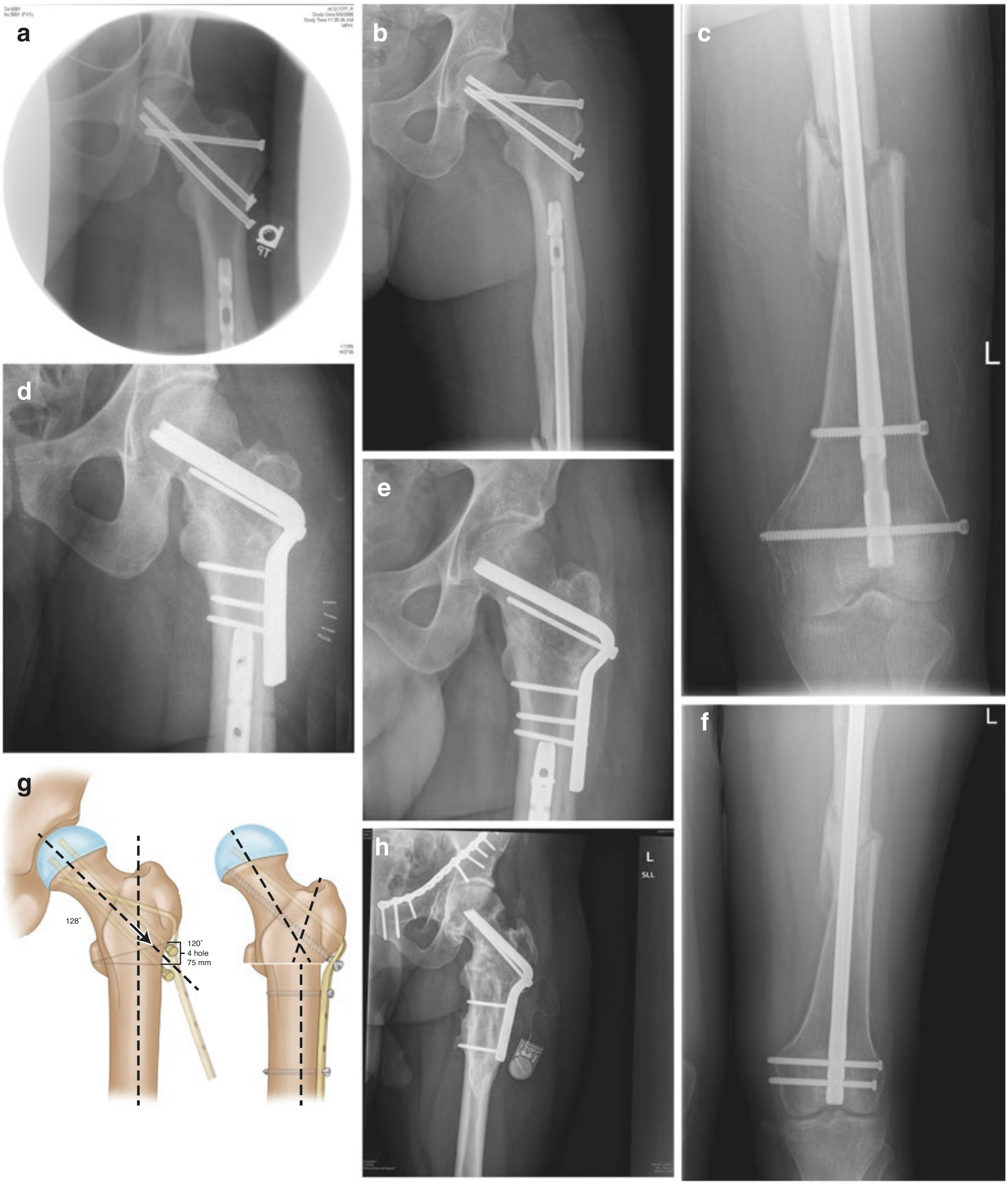

Fig. 41.4 Nonunion of the femoral neck. A 23-year-old man suffered an ipsilateral femoral neck and shaft fracture in a motorcycle accident. The shaft fracture was treated with a retrograde nail, and the vertical neck fracture was treated with cannulated screws. (**a**) Initial C-arm view of the femoral neck fixation shows imperfect reduction. (**b**) By 4 months post-op, the neck has fallen into varus and shortened. In this situation, the femoral neck will not heal and will continue to displace. (**c**) The femoral shaft is ununited at 4 months as well. (**d**) Valgus intertrochanteric osteotomy is performed for the femoral neck nonunion, and exchange nailing for the femoral shaft nonunion. (**e**) and (**f**) Four months after surgery, both nonunions are healed. (**g**) Example of a osteotomy procedure plan for this osteotomy on a different patient. (**h**) Example of 8-year follow-up on a patient who had this same procedure

Principles of plate fixation for nonunion are like those for plate fixation of acute fractures, with the caveat that additional stability is usually required due to the longer time often required for healing. Gentle soft tissue handling is always important, but in nonunion surgery there is often scar tissue that hampers exposure. There will always be some stripping involved and the bone surface of hypertrophic nonunions may need to be contoured to allow plate fit. When possible, use submuscular placement techniques and percutaneous screw placement to get plate length proximal and distal to the NU site. Exposed bone near the NU site may be drilled, "feathered," or decorticated with an osteotome to stimulate the healing response on the periosteal surface. If the intramedullary canal can be opened during debridement of an infected, atrophic or synovial nonunion, that should be done to allow the endosteal blood supply access to the NU site. However, hypertrophic NUs should not be "taken down" for that purpose, unless it is needed for alignment correction. Correct alignment in three planes is necessary not only for function, but for stability and for healing. The use of a femoral distractor on the concave side and a lamina spreader in the defect may help with alignment correction [46]. Plates should be positioned on the tension side of the bone when anatomy allows and should be placed under tension across the nonunion, using the articulated tensioning device for larger fragment plates, or a push-pull screw with a Verbrugge or Farabeuf clamp. Dynamic compression plate holes should be utilized when available [47]. Dual plating may be necessary to enhance stability but beware the damage to the vascularity of the bone. Do not order the dead bone sandwich! When adding a second, supplemental plate to protect alignment (e.g., medial distal femur or proximal tibia), attempt to use a smaller, strategic implant placed in buttress mode through a minimally invasive approach on the opposite side from the tension plate. In the distal humerus, two plates are almost always necessary to stabilize both the medial and lateral columns. For metaphyseal nonunion, such as in the proximal tibia, locking plates may be necessary to achieve adequate grip on the peri-articular fragment, but be careful that locking on both sides of the NU does not compromise compression across it. At either end of the femur, 95° blade plates are excellent devices for fixation, compression, and alignment correction of metaphyseal nonunion.

Nonunion of the femoral neck is an example of a situation in which improved stability and correction of mechanical alignment, in combination with biological factors, can lead to reliable healing. Displaced femoral neck fractures are at high risk for nonunion due to several factors, including intra-articular environment, retrograde blood flow, lack of periosteal envelope, and prominent mechanical shear forces at the fracture site. For this reason, in younger more active patients, they require anatomic reduction and stable fixation to achieve union. When nonunion or loss of fixation occurs after treatment, the hip can sometimes be saved and union achieved with intertrochanteric valgus osteotomy as described by Pauwels. In this procedure, a laterally based wedge is removed from the intertrochanteric region of the proximal femur, which results in a valgus tilt to correct the varus deformity and shortening of the nonunion. It is most reliably fixed with a blade plate. The procedure has a high rate of success at achieving union and can successfully restore hip function even in the face of some degree of avascular necrosis of the femoral head, provided there is no collapse of that head (Fig. 41.4) [48–50].

41.8 Surgical Treatment of Malunion

Entire fellowships are devoted to this topic and detailed instruction is beyond the scope of this chapter. The stages of the process include analysis of the locations and degrees of deformity; planning the sites, orientations, and magnitudes of osteotomies; and fixation options. It is very important to understand the significance of the deformity to the patient's functional demands and desires and to have in-depth discussion of outcomes and risks. It is devastating to turn an annoying or cosmetic malunion into a disabling nonunion, or worse, and infected nonunion.

Perhaps the simplest situation is an angular malunion of a long bone diaphysis. Figure 41.5

Fig. 41.5 Oblique osteotomy of tibial malunion. (**a**) A 28-year-old man with a varus tibial malunion following intramedullary nailing of his proximal third fracture. The malunion resulted from an improper starting point for the tibial nail. (**b**) After hardware removal, Schanz pins are placed parallel to the knee and ankle joints. The osteotomy is performed, and the femoral distractor is used to bring the pins parallel to each other. (**c**) Diagram from Sanders et al. showing the location and orientation of the osteotomy (reused with permission from [52]). (**d**) After performance of the osteotomy, a clamp is placed across the bone cut. (**e**) Intraoperative radiograph showing parallel alignment of the knee and ankle, and placement of lag screws across the osteotomy. (**f**) Final fixation, with a neutralization plate placed on the tension side

represents an example of an angular malunion of the tibia (Fig. 41.5). The magnitude of tibial deformity which would require surgical correction is somewhat controversial and various criteria have been published. The patient tolerance for angular malunion of the tibia is variable based on patient's age, activity, normal alignment, and occupational or recreational requirements. In general, valgus angulations <10°, varus angulations <6°, extension/flexion angulations of <10°, and malrotations of less than 10° are well tolerated by most patients. A detailed history of the patient's complaints, and careful physical exam including measurement of length discrepancies and observation of gait or simulated sport activity is important to formulate the goals of treatment. Assessment of soft tissue envelope health and vascular status will help with defining risks of the procedure. Radiographs usually necessary include at least AP and lateral views of both tibiae including knee and ankle. Long standing films may be useful in evaluating overall alignment. Rotation can usually be evaluated from physical exam although CT scan may be helpful.

Corrective osteotomy can be done with a variety of surgical techniques, including opening wedge, closing wedge, dome, clamshell [51], or single-cut oblique [52] methods. A closing wedge provides correction of angulation and rotation, and the opportunity for compression but may lead to shortening and a limited bony surface for healing. The opening wedge requires bone grafting and may lead to healing problems, particularly in the tibial diaphysis after previous fracture. The dome osteotomy is technically difficult to perform and limits the ability to correct rotation or multiplanar deformity. The single-cut oblique osteotomy can correct multiplanar deformity including rotation and allow some lengthening, while providing large bone surfaces to compress. Planning of the osteotomy has been detailed in the literature [52, 53] and can be done using trigonometry, or with computer-assisted planning, or by utilizing the "no-angulation view" technique. It should be understood that the orientation of the osteotomy has a transverse component and thus correction through the cut will always entail some degree of rotation; it is essential that the obliquity of the cut be performed in the correct orientation to improve and not worsen any rotational component of the deformity. The femoral distractor is a useful adjunct to gaining length, and an appropriately performed lag screw at the axis or correction is a helpful component for healing. Ten of 12 patients who underwent oblique osteotomy of a tibial malunion healed at an average of 4.5 months and had resumed full weightbearing, activities of daily living, and light work. Two noncompliant patients failed the operation due to soft tissue or hardware failures; both were salvaged and returned to original employment eventually [52]. Axial lengthening in this series was modest and somewhat disappointing, averaging 1.3 cm. The maximal lengthening obtained was 2.5 cm, and the authors recommend that if more than that is required, then alternative methods such as distraction osteogenesis should be considered.

41.9 Bone Grafting

Bone grafting is indicated when there is a gap or defect in the bone from injury or debridement, or when there is an atrophic/oligotrophic nonunion requiring biologic stimulation. Hypertrophic nonunions and malunion osteotomies rarely need any bone graft. Bone grafts are classically considered to perform three primary functions: osteoinduction, osteoconduction, and osteogenesis—formation of bone by living cells. In addition, cortical or cortico-cancellous bone grafts can perform a structural function; and when they are transferred along with a vascular pedicle, they can bring new blood supply to a non-united area. Bone grafting is usually performed as a component of surgical treatment that may include fixation or re-fixation, debridement, re-alignment, and bone stimulation. It is rarely performed as a standalone procedure, except in the case of segmental defects, or as a prophylactic treatment in high energy open tibia fractures.

The classic nonstructural bone graft is cancellous bone harvested from the iliac crest with curettes, osteotomes, or an acetabular reamer [54]. In recent years, intramedullary bone has been harvested from femurs or tibias using a device called a Reamer Irrigator Aspirator or RIA (DepuySynthes, West Chester, PA). The RIA has been shown to provide increased volumes of bone graft in shorter times, with less donor site pain, compared with both anterior and posterior iliac crest bone graft techniques using curettes and gouges. There was no significant difference in healing rates or time required for healing although the study was under-powered [55]. Some authors have found differences in growth factors and osteogenic elements between iliac crest graft and RIA graft [56]. Fracture of the donor femur and perforation of the anterior cortex of the donor femur are serious complications that can occur with RIA bone harvest, and the risk of such events can be lessened by certain technical factors, such as monitoring the reamer tip with fluoroscopy through the harvest.

When placing cancellous graft for stimulation of atrophic nonunion or consolidation of gaps, the graft should be placed in contact with living bleeding bone on both ends, and it should overlap the ends of the bone. When possible, the intramedullary canal should be opened on either side of the nonunion (usually done before application of fixation). The periosteal surface should be scored or feathered to open small vascular channels in the bone where you wish the graft to anchor. The graft should be held in place by a healthy soft tissue envelope. The classic example is the posterolateral bone graft of Harmon for tibial nonunion [57]. A recent report of 59 procedures revealed a success rate of 75% [58]. In this procedure, the graft is placed on the intermuscular septum between the tibia and fibula, under the posterior calf musculature. The graft is in contact with the surface of both the tibia and fibula (appropriately prepared), and the goal is to create a bridging synostosis between the two bones that spans the nonunion site. Video of this technique is available online from the OTA video library at: https://vimeopro.com/orthotraumaassn/2015-surgical-technique-videos/video/187360686 (Fig. 41.6) An alternative approach going anterior to the fibula has been called “central bone grafting” [59] and may be somewhat easier due to supine positioning.

When the patient has inadequate donor bone graft sites to provide enough autograft cancellous bone, there are some choices for expander or substitutes (Table 41.2). Some bone graft substitutes are primarily osteoconductive, that is, they provide a three dimensional scaffold that allows ingrowth or on-growth of host bone. In general, these are used to fill metaphyseal defects and support subchondral bone near a joint, or for use in non-segmental defects. Their use in nonunions is primarily as a volume expander for autogenous cancellous graft. These products include calcium phosphates and calcium sulfates (Plaster of Paris), collagen-based matrices, bioactive glass, and coralline hydroxyapetite [60, 61]. Allograft cancellous bone is available in most hospitals and can also provide a scaffold for osteoconduction. The live cells and growth factors are removed during processing for sterilization, and so there is no osteoinductive capability in this product. There is a very low possibility of disease transmission with allograft bone. It can be combined with bone morphogenic protein (BMP) to increase the efficacy as an autograft substitute [62]. Demineralized Bone Matrix (DBM) products have been available for decades. They are available in the form of a gel, paste, putty, or powder. DBMs have some degree of osteoconduction property and provide an osteoinductive stimulus function through growth factors. The efficacy of these products has been highly variable in the many studies that have been done, and their use is still controversial. Recombinant human BMP (rhBMP-2 and rhBMP-7) has been used to enhance healing in fracture and arthrodesis, particularly in the spine. It does not seem to add any additional benefit when combined with iliac crest autograft [63], but, as mentioned above, it may be a useful *alternative* to ICBG if that is unavailable, particularly when combined with allograft. Calcium phosphates and sulfates are void fillers with primarily osteoconductive properties. They can be used in cement form to increase structural integrity of osteopenic bone and improve screw purchase. In addition, because the body slowly absorbs them, they have been used for antibiotic delivery.

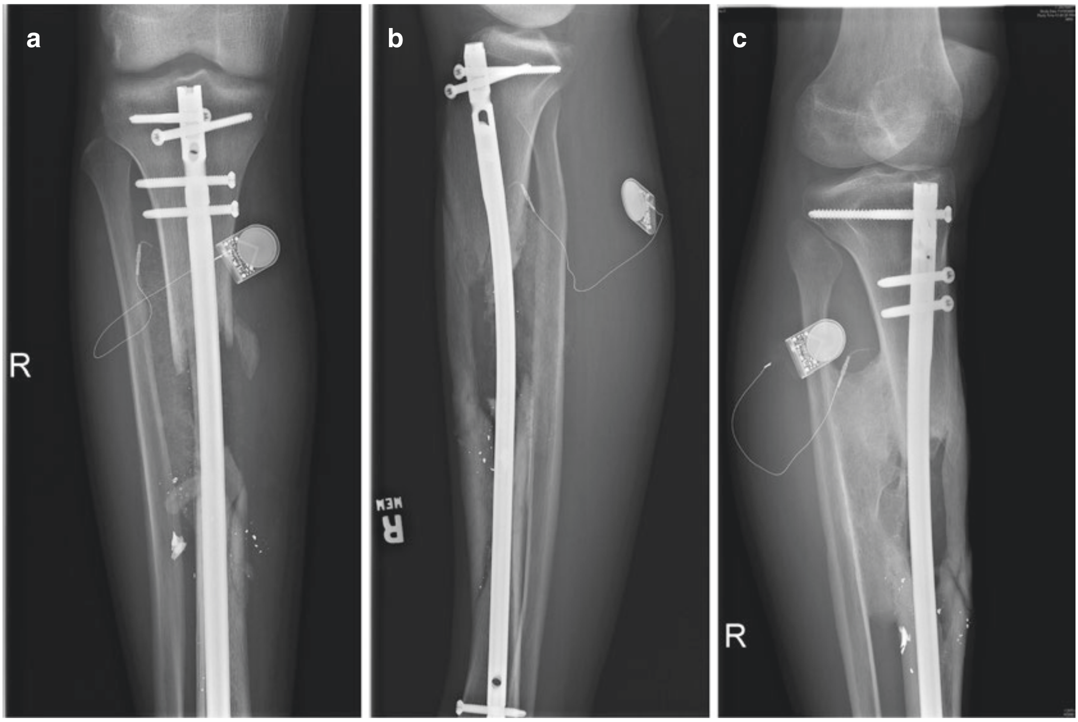

Fig. 41.6 Posterolateral bone graft for tibial nonunion. A 23-year-old male suffered a gunshot wound resulting an open grade III-B tibia fracture with significant segmental tibial bone loss. After an initial period of external fixation and wound care, he underwent reamed intramedullary interlocked nailing. After wound healing and soft tissue recovery, he underwent a posterolateral bone graft and implantable bone stimulator to address the defect in the tibia. (**a**) Anteroposterior radiograph 1 month after bone grafting. (**b**) Lateral view after bone grafting. (**c**) Oblique view at 4 months showing a solid tibio-fibular synostosis

Table 41.2 Bone graft substitutes, expander, and enhancers

Material	Role	Pro	Con
Cancellous allograft	Osteoconduction, filling of metaphyseal defects, expansion of autograft volume	Three-dimensional structure of human cancellous bone	Slow and variable rate of incorporation, no osteoinduction or osteogenesis, low risk of disease transmission, requires specialized storage
Demineralized bone matrix (DBM)	Osteoconduction, osteoinduction	No limits to quantity, easy storage, variety of structures and forms	Variability in effectiveness due to variability in source bone and manufacturing processes, low risk of viral transmission
Recombinant human bone morphogenic protein (BMP)	Osteoinduction	No limit on quantity, relatively easy to store	Inflammatory response, expense, uncertain efficacy
Ceramics: calcium phosphate/sulfate, tricalcium phosphate, hydroxyapatite	Osteoconduction; filling of metaphyseal defects, expansion of autograft volume; limited use in nonunion	No limit of quantity, no risk of morbidity or disease transmission, easy sterilization, and storage	No osteoinduction or osteogenesis; variable resorption rate
Combination products			

When there is segmental defect in the bone either from trauma or debridement, it can be handled by shortening the bone, transporting bone (the technique of Ilizarov), or by grafting the defect. The two grafting techniques that are most commonly used are vascularized bone transplant (e.g., free fibula transfer) or cancellous grafting using the technique of Masquelet [64, 65]. In this technique, the nonunion site is debrided and the defect is filled using polymethylmethacrylate (PMMA) cement containing antibiotics. This cement spacer is formed to fit the gap and to surround the ends of the bone, which is commonly stabilized with an external fixator, although plates and nails can be used as well. The PMMA spacer induces the formation of an investing membrane that produces various growth factors that favor bone formation. After approximately 6 weeks, the site is opened, taking great care to preserve the membrane, and the spacer is removed. The gap is then filled with bone graft, obtained from the iliac crest or by RIA, the membrane is closed around the graft, and definitive fixation is applied. The largest series of cases reported in the literature consisted of 84 patients who achieved 90% union at 1 year [66]. A systematic review of the literature regarding this technique published in 2016 revealed an 89% success rate in achieving union, and a 91% success rate in treating infection [67]. However, some smaller series have shown lesser rates of success and higher rates of complications, indicating the overall general high complexity and risk of segmental defect treatment.

41.10 Implantable Bone Stimulator

Implantable electrical bone stimulators have been used for treatment of nonunion and for augmentation of spinal fusion. This device (Osteogen bone growth stimulator, Zimmer Biomet, Warsaw, IN) consists of a small implantable battery ("generator") with the anode on the body of the battery and a titanium filament cathode. Once implanted in the aqueous environment of the body, the circuit is completed and a small current flows through the tissues. This is usually implanted as the last stage in the procedure, after failed hardware is removed, debridement is performed, nonunion surfaces are prepared, re-fixation is performed and bone grafting in place. The cathode wire or mesh can be folded or coiled and inserted into drill holes, troughs, or nonunion defects. Some part of the cathode should contact living bone on both sides of the nonunion, and it should not come into contact with other metallic implants. The cathode wire can be buried in bone grafts, wrapped around cortical, or matchstick grafts or inserted into drill holes in the bone. The generator is then positioned in a subcutaneous pocket that is created in a location that will not be bothersome to the patient and will not obscure radiographs of the nonunion. It is usually in a superficial enough location for palpation to facilitate removal. Removal is recommended and can usually be performed as an outpatient or office procedure with local anesthesia. This can be performed at 9–12 months as an elective procedure after healing is achieved. The battery wire will break loose at the cathode connection with gentle steady tension.

There are no prospective randomized controlled trials of implantable bone stimulator use in nonunion. An uncontrolled prospective multicenter trial and a retrospective single surgeon series both showed approximately 85% success rate in heterogenous groups of long bone nonunions [68, 69]. A retrospective study comparing NU treatment with and without implantable bone stimulator utilized the practices of two orthopedic traumatologists with similar training and experience, who were partners. There were 38 patients with a minimum of 1-year follow-up. Twenty-five did not have an implantable bone stimulator and 13 did. The use of an implantable bone stimulator was found to be significantly associated with increased rate of union (Fig. 41.7) [70].

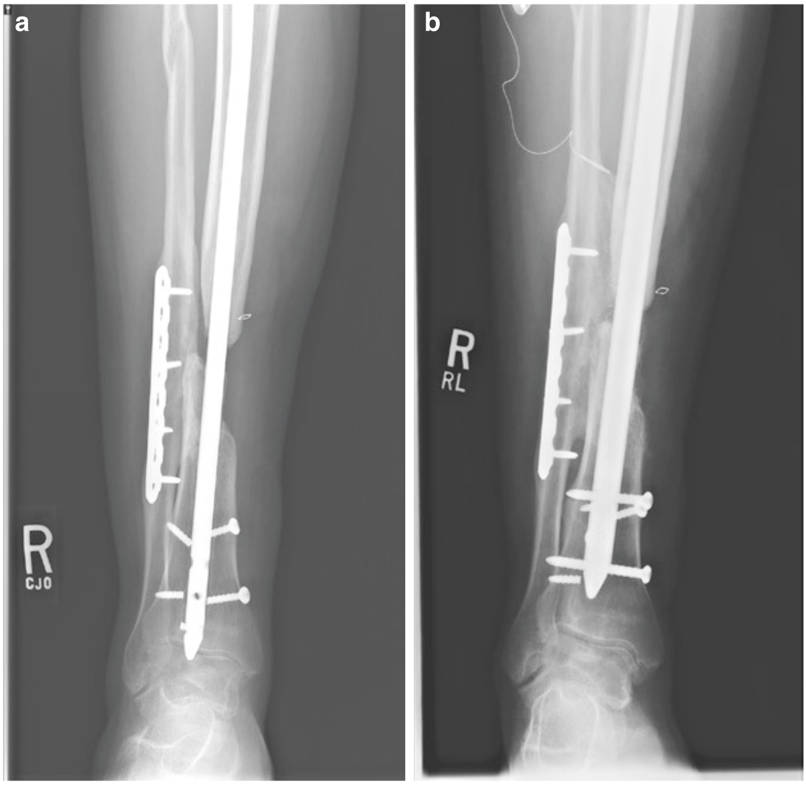

Fig. 41.7 Implantable bone stimulator. (**a**) A 24-year-old patient suffered an open tibia fracture with bone loss that required a soft tissue free flap. He was initially treated with unreamed nailing. Five years after his injury, the fibula had healed but the tibia had not, and the interlock screws failed. (**b**) He was treated successfully with exchange nailing, posterolateral bone grafting, and implantable bone stimulator

41.11 Conclusion

Treatment of a nonunion or malunion is a complicated, long-term process that requires intimate knowledge of the patient's medical and surgical history, as well as personal and social history. The surgeon needs to know the patient's occupation, living situation, social and psychological support structure, hobbies, sports, expectations, hopes, and fears.

Key Concepts

- Medical conditions should be assessed and optimized as part of the treatment. This includes endocrine and metabolic work-up, investigation for occult infection, management of diabetes and vascular disease, nutritional assessment, addressing medications or habits (tobacco) that may inhibit healing, and evaluation of limb function and soft tis-

sue envelope. Optimization of these host factors is the first step in treatment of any patient.
- Non-operative treatments, such as bone stimulators, can work in selected patients. They are particularly suited to hypertrophic nonunions of the lower extremity with good alignment.
- When non-operative treatment of the condition is not successful or appropriate, surgical treatments can be effective and can be offered to the patient, after thorough discussion of risks and benefits. The surgeon should be experienced with a wide range of surgical treatment options and have an understanding of the outcomes. When appropriate, referral to a center with more experience in these complex treatments is advisable.

Take Home Messages
- Surgical treatment is based on an individualized assessment of the patient, the limb, and the bone. It may include revascularization or flap coverage in addition to orthopedic procedures such as hardware removal, debridement, correction of alignment, stable internal fixation, and bone grafting or other healing adjuncts.
- The goal of internal fixation of nonunion is to compress the fracture lines and increase the stability of the construct. This may often require longer/larger/more implants applied in a rational and biologically friendly manner. Analysis of previous fixation failure will often guide the way to surgical strategy.
- Hypertrophic nonunions usually heal well with just improved stability via internal fixation.
- Bone grafting is useful when the nonunion is atrophic, or there is a bone gap or defect. Graft can be obtained in a variety of ways from the pelvis or intramedullary canal of long bones (RIA). Bone graft substitutes or expanders can be useful, but autograft remains the gold standard for use in nonunion.
- Treatment of a functionally significant malunion requires osteotomy. This can be performed using opening or closing edge, dome, clamshell, or oblique single-cut techniques. Appropriate planning is essential.

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