Special Techniques for Nonunions Associated with Traumatic Bone Loss

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15.1 Introduction

The reconstruction of long bone defects is often a major challenge in limb salvage regardless of the etiology of bone loss. There is limited high-grade evidence on the efficacy of multiple techniques for bone regeneration and especially on comparative outcomes of different management techniques. The literature is rife with limited case series and single surgeon experiences that do not provide evidence-based treatment recommendations. Nonetheless, bone loss remains a common problem for clinicians, and multiple approaches are utilized depending on surgeon experience and resources. To a certain extent, defect size dictates many of the treatment approaches. Small, stabilized defects (2–3 cm) are frequently treated with acute cancellous autograft application. While this may be effective in favorable (i.e., well vascularized) healing sites, this is not typically used for larger defects (greater than 4 cm). In large defects, the healing is unpredictable, and significantly, larger bone graft volumes are necessary which leads to concerns about graft absorption [1]. Therefore, in large defects, specialized approaches are required. The most common classic techniques are vascularized free bone transfer and Ilizarov bone transport. Both of these techniques require specialized training or equipment and a high level of surgical expertise in conjunction with postsurgical resources and support. Significant patient compliance and cooperation are required, and very large defects require protracted treatment times. Despite these limitations, these are powerful techniques for bone regeneration, and the results can be remarkable. In many situations, neither vascularized transfer nor bone transport is optimal or available, and novel techniques are being utilized. The induced membrane technique (Masquelet) is increasingly utilized in bone defects to extend the application of cancellous grafting to larger defect sizes. This technique has been well reviewed in the literature [2–4] and is utilized with increasing frequency for massive defects. Even more novel approaches to defects include the use of spinal cages (for graft containment and structure support) and noncustom porous tantalum implants (for structural support and defect substitution). These more unique approaches await systematic evaluation but do provide solutions in recalcitrant cases.

15.2 Distraction Osteogenesis

The concept of distraction osteogenesis as a method of skeletal reconstruction can be traced back to as early as 1905. This has been done with a variety of methods including osteotomy and

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immediate traction, external fixation, internal fixation with either intramedullary rods or extramedullary osteosynthesis, and fine wire fixation. Significant bone loss occurs in a minority of fractures (0.4%) but that is significantly higher in cases of open fracture and when planned intervention demands resection of large segments of bone [5]. Each case of bone loss carries an individual character that is comprised of the patient demographics and comorbidities along with the injury itself. In the presence of an acute open fracture, the key concepts include soft tissue compromise and instability. In the case of tumor, the demands of cancer treatment and medical compromise of the patient have significant impact on the planned intervention for bone loss. Infection and nonunion include both concepts of soft tissue compromise along with inflammation and bone loss. The ultimate treatment for any of these situations would include resection and bone grafting with a source that provides cortical stability and rapid integration into the human skeleton without risk of infection or rejection. Unfortunately, there are no current interventions that can achieve these idealistic goals. However, the use of distraction osteogenesis remains the closest to this potential gold standard. With the use of corticotomy and distraction, the donor source risk is minimized as the graft is a similar shape and has a robust soft tissue envelope providing biology to the healing environment.

Distraction osteogenesis refers to the formation of new bone between two ends of vascularized bone that are gradually distracted [6]. This can be accomplished through multiple methods of distraction. This concept was first introduced in 1905 by Codivilla, who performed the first successful limb lengthening by osteotomy and immediate transcalcaneal traction [7]. In 1913, Ombredanne reported the fist use of external fixation for distraction. This was improved upon by Putti in 1921 who utilized a monolateral fixator at a rate of 2–3 mm/day as opposed to the 5 mm/day used by the sentinel author [8]. These concepts have been applied to many different clinical scenarios with variable success and complication. After World War II, Ilizarov began to develop the concept of distraction through the use of fine wire attached to circular frames. This imparted stability and allowed for limb salvage for many limbs that would have otherwise undergone amputation (Fig. 15.1). This was done out of necessity as he faced a community of patients in Siberia where antibiotics were scarce, osteomyelitis was common, and amputation led to poor outcomes [6, 9]. The additional capacity to correct deformity while concurrently treating bone loss remains unparalleled; however, the technical challenges for the surgeon and the practical difficulties for the patient continue to limit the use of this technique. The current section discusses the use of fine wire circular fixation, unilateral rail distraction, distraction over intramedullary devices, and distraction with plate osteosynthesis as unique treatments for bone loss.

15.2.1 Fine Wire Circular Fixation

External fixation has distinct advantages with respect to the ability to avoid direct instrumentation at sites of infected nonunions and also with the ability to slowly correct deformity, which potentially can limit the risk of injury to structures at risk. Fine wire circular fixation remains a powerful tool for both the correction of deformity and the application of distraction forces that allow for deposition of new bone. The most critical components linked to this remain to be the handling of the soft tissues during treatment (Fig. 15.2). The surgeon might choose the use of fine wire circular fixation in the setting of a nonunion that involves bone loss and angular deformity. All external fixator systems allow for multiple planes of freedom, but the use of fine wire circular fixation is the only system that allows for both elastic control and dynamic control that respect bone biology. When an in-line or even multiplanar fixator is utilized with half pin fixation alone, there is not just control of length imparted but a distinct lack of control of angulation. This lack of control is considered “parasitic” to bony healing as it is uneven and nonbiologic. With the use of fine wire fixation, the stability that is imparted will allow for healing by secondary intention and callous formation

Fig. 15.1 31-year-old male who suffered a moped accident with an isolated complex open intraarticular distal tibia and fibula fracture. He underwent staged management and with debridement and spanning external fixation, followed by open reduction internal fixation of the articular block and application of antibiotic impregnated beads until he healed a free latissimus flap. 5 cm of bone loss was then healed using a distraction osteogenesis technique with a proximal corticotomy in a multiplanar external fixator. The patient went on to consolidate the regenerate and heal the docking site without need for bone grafting, despite severe noncompliance with care. He currently walks without assistive device and has since had his distal tibial hardware removed due to a late infection due to shoewear breakdown of the free flap

Fig. 15.2 Clinical photograph of a 38-year-old male who suffered a motorcycle collision with a complex Gustilo and Anderson type IIIB open proximal tibia fracture with 10 cm of proximal tibial bone loss. This patient required careful debridement, open reduction internal fixation, and massive autologous bone grafting using a Masquelet technique after a free flap successfully healed. He ambulates without assistive device at 2 years post-reconstruction

but will at the same time limit the "parasitic" lack of control of angulation [10].

The more popularized understanding of fine wire fixation is that it can be used in conjunction with independent distraction–compression devices that will allow for multiplanar correction of deformity by application of compression in one plane and distraction in another.

The use of fine wire circular fixation has been successfully utilized in many clinical series as outlined above to achieve restoration of skeletal alignment and length. The cost and complexity associated with these types of systems can, however, be burdensome and has lead many surgeons to unilateral frames due to the ability to achieve skeletal success and simplify the process for both the surgeon and the patient.

In this technique, the nonunion site is debrided of all nonviable tissue and bone after the removal of any preexisting internal fixation devices. A unilateral frame can then be applied in a monofocal or bifocal method. In the monofocal method, compression and distraction is initiated at the fracture site to stimulate osteogenesis. Distraction can then also be done at the nonunion site to restore leg length. If a bifocal method is done, the distraction is achieved outside of the nonunion site.

This is a widely used technique in all long bones. Harshwal et al. recently presented a series of 37 patients (7 femur and 30 tibias) all treated for nonunion within the first 8 months of the injury. Rate of union was reported at 91%. Minimal complications were noted, primarily those of pin-tract infections. These results are consistent with those reported by other authors [4, 11, 12].

15.2.2 Distraction Over Intramedullary Nails

15.2.2.1 Intramedullary Device Plus External Fixation

Given the technical difficulties of controlling transport segments during distraction osteogenesis with purely external fixation, fine wire, or Schanz pin devices, the idea of guidance of the transport over intramedullary devices has become appealing. In addition, the angular deformities introduced by the use of a unilateral rail fixator alone, in conjunction with the inability to be fully weight bearing, have demanded the ability to guide a correction over an intramedullary device.

In a recent series, Gulabi altered the original descriptions of other authors to utilize acute compression and distraction osteogenesis. These patients were all tibial diaphyseal fractures with bone loss. Custom intramedullary nails were utilized with multiple locking hole options. In this technique, the bone loss site is cleared and a distant metaphyseal corticotomy is made that liberates a transport segment. The bone loss segment is shortened up to 5 cm, and the corticotomy site is compressed. The transport then proceeds at 2 mm/day, and when docking is achieved, the site is bone grafted from the iliac crest. Their results demonstrated radiographic union, no angular deformity, a moderate amount of pin site infections, and a 0.4 external fixation index (number of months external fixator system worn divided by centimeters of distraction) [13].

15.2.2.2 Telescopic Intramedullary Restoration of Length

The problems associated with lengthening over an intramedullary nail are consistent with external fixation problems in general. These include pin-tract infections, scarring, pain, and patient comfort. In order to obviate these problems, several entirely intramedullary devices have been developed with the goal of using an internal lengthening mechanism to provide distraction osteogenesis. The intramedullary skeletal kinetic distractor (ISKD, Orthofix Inc., McKinney, TX, USA, and the PRECICE intramedullary nail (Ellipse Technologies, Irvine, CA, USA) utilize novel techniques of lengthening from within the canal (Fig. 15.3).

The ISKD Nail utilizes two internal rotating clutches to advance a threaded rod within the nail that is attached to the distal segment beyond an osteotomy with interlocking bolts. This provides distraction that is based on typical activities of daily living that provide stimulus through 3–9 degrees of rotation through the osteotomy site. There have been many challenges with this device including a lack of absolute control of distraction. This can be due to variable activities of patients, but can lead to a rate of distraction that is suboptimal, either too fast or slow [14, 15].

The PRECICE nail uses an externally applied magnetic device to control the lengthening. The proposed advantages to this include the ability to not only monitor the lengthening but also change the prescription of lengthening based on optimal conditions and the regenerate response time. There is less clinical evidence regarding this device but results appear similar to the ISKD with unique difficulties encountered [16, 17].

With respect to critical cortical defects and nonunion, these devices can be utilized for either compression of a fracture site or distraction osteogenesis. If a defect is predicted, this can be used to compress the fracture and then to perform an osteotomy and distract healthy bone to attain regenerate.

Fig. 15.3 55-year-old male who underwent en bloc resection of the femur for malignant fibrous histiocytoma 20 years prior to presentation. The intercalary allograft femur had healed with limb foreshortening that lead to extensive back pain and hip arthritis. Staged management included restoration of standing balance with intramedullary nail extraction and application of an intramedullary telescopic nail with proximal corticotomy through native metaphysis. At 6 months, post-op patient was pain free at the *upper thigh* and underwent a total hip arthroplasty with concomitant removal of hardware at 1 year

15.2.3 Distraction with Plate Osteosynthesis

The use of intramedullary nails in conjunction with external fixator distraction can be complicated by pin site infection that can develop into an intramedullary infection due to the proximity of the pins and the nail. It is also limited by the ability to apply transport to a proximal or distal fracture. Oh et al. [18] recently reported the use of locking plate stabilization with external fixator generated distraction osteogenesis. In their series of ten patients, a similar technique of corticotomy is performed, and after a latency period, distraction proceeded with 1 mm/day. When the docking site is achieved, the transport segment is stabilized with screw fixation through the plate, the docking site is grafted, and the external fixator is removed. All patients achieved radiographic union, and complications involve pin site infections only. Theoretically, these patients might be at higher risk for fracture of regenerate bone, although this has not occurred for them at the time of publication. The primary advantage is the ability to stabilize the transport segment and remove the external fixator despite a lack of radiographic union. The disadvantage is theoretically the lack of loadbearing the plate can contribute. However, the advantages of being able to apply this technique to skeletally immature patients, large amount of bone available for placement of external fixation, and decreased time to removal of external fixation can outweigh these disadvantages (Fig. 15.4).

15.3 Masquelet Technique

The induced membrane technique is a unique alternative to acute bulk grafting. This technique was originally utilized for regeneration of diaphyseal defects, but use has been expanded to metaphyseal defects as well. Professor Masquelet developed the technique in early 1984 and soon after initiated a clinical study to demonstrate its efficacy [2].

Fig. 15.4 14-year-old male who underwent resection for osteosarcoma with limb foreshortening and flexion contracture of the knee. Distraction with plate osteosynthesis utilized with proximal tibial corticotomy highlighted (*yellow arrow*) to the *left*. External fixator removed at 7 weeks and consolidate locked into the plate construct distally. Allowed for 4.6 cm of distraction in 63 days of external fixation. Consolidation of regenerate noted to be complete by 4 months *on the right*. (Courtesy of Chang-Wug Oh, MD, Kyungpook National University Hospital, Daegu, Korea)

Key Features

- A bioactive membrane is created by placement of a Poly(methyl methacrylate) (PMMA) block into a clean, debrided defect (Fig. 15.5).
- The blood supply around the induced membrane is left intact or optimized by free tissue transfer.
- The induced membrane is incised, and the PMMA block is carefully removed, leaving the membrane intact as a protective and supportive grafting bed.
- Slow consolidation is observed, and weight bearing is restricted until union [2].

15.3.1 Membrane

The induced membrane is believed to be a unique property of this technique and critical to its success. Extensive animal evaluations in both small and medium animal models have demonstrated the membrane is made of a type I collagen-heavy matrix and fibroblastic cells. The membrane itself has tissue level organization with an inner aspect of epithelial-like fibroblasts and collagen bundles that run parallel to the surface of the membrane. This tissue is well vascularized and contains a high concentration of vascular endothelial growth factor. Typically, a solid block of PMMA is used to produce the spacer; this induces a mild foreign-body inflammatory response with giant cells and macrophages. The inflammatory response slowly decreases over time following spacer implantation may disappear by 6 months following bone grafting. Tissue from these membranes has been analyzed using molecular techniques including immunohistochemistry, and these studies demonstrate expression of proteins associated with induction of new bone formation. Thus,

Fig. 15.5 The forceps are holding the induced membrane which has been opened longitudinally and provides vascularized pouch for graft material

many feel that these membranes are bioactive. In addition, the induced membrane also acts to eliminate soft tissue interposition into defects and created a protective cavity to accept bone graft. The shape and size of the healed bone graft are defined by the membrane [2, 19–22].

15.3.2 Technique

By definition, this is a two-stage technique. The first stage is akin to a tumor debridement with aggressive removal of nonviable bone, scar, and any damaged or nonviable local soft tissues. The bone debridement cannot be limited since frequently bone necrosis at the fracture edges has progressed significantly proximal to the defect. After debridement/resection, the remaining bone ends should be healthy with a viable bleeding bed (Fig. 15.6). In the setting of a severe soft tissue deficit or wound problem, standard dead space management techniques using PMMA bead strands can be used, while the preliminary wound management is performed. Open wounds can be managed with negative pressure therapy or bead pouch depending on the individual patient need. Once the soft tissue bed is clean and mature, the definitive solid spacer can be placed with simultaneous muscle coverage.

When feasible, intramedullary reaming is performed ot aid in the debridement of the intramedullary canal and to stimulate an endosteal healing response. For optimum membrane induction and better stability of the construct, the cement should be placed inside the canal (when feasible) and over the edges of the native bone (wrapping) and should fill the space of defect. While external fixation was utilized in the original technique, more stable forms of internal fixation are typically utilized, even intramedullary nails. Use of intramedullary nails can decrease required graft volumes and provide long-term stability in these slowly healing constructs. Finally, optimal soft tissue blood supply is requisite around the induced membrane zone. Free tissue transfer is far optimal to a tight primary wound closure especially in the mid-to-distal tibia.

15.3.3 Outcomes

The original Masquelet series of 35 patients with upper and lower extremity segmental defects that measured 4–25 cm in length reported a 100% healing rate. Most of these were treated with external fixation and many had free flaps. The mean time to full weight bearing was 8.5 months [23]. While this series is impressive, it likely does not represent contemporary use of the technique. Subsequent reports have included the use of bone morphogenetic protein (BMP), reamed intramedullary grafts, and multiple modes of internal fixation—for most of these techniques, ultimate union rates hover around 90% [2, 24, 25]. While many of these publications report good results, overall the level of evidence for this technique remains low since these are mostly retrospective case series or small prospective noncomparative studies.

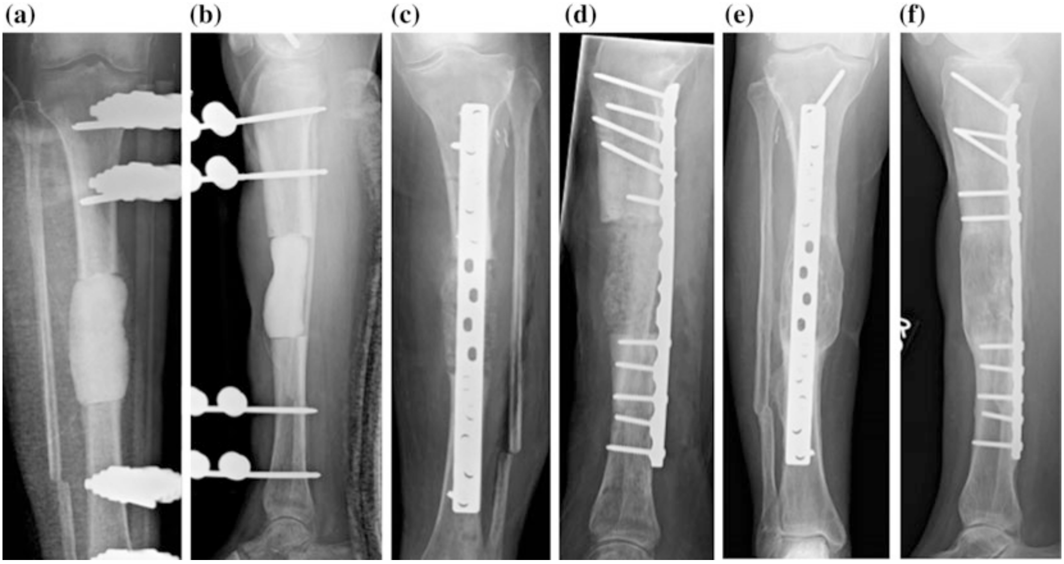

Fig. 15.6 Diaphyseal infection undergoes aggressive resection and debridement. **a, b** The defect is filled with PMMA, and preliminary stabilization is achieved with external fixation. **c, d** Classically, the ends of the bone are over wrapped with PMMA. At 8 weeks, the wound is filled with cancellous autograft and BMP and formal plate fixation is utilized. **e, f** At 6 months, the regenerate is completely healed and the patient is weight bearing

15.3.4 New Considerations

The timing of bone grafting into the membrane has been recently evaluated [26]. While contemporary approaches demonstrate large variability in timing of secondary cancellous grafting into the membrane bed, most surgeons delay 6 weeks or more after placement of the spacer. A closer evaluation of one of the original animal studies demonstrated the time course of growth factor expression from induced membrane samples with quantitative and qualitative immunohistochemistry [20]. Maximum BMP-2 levels were seen at 4 weeks post-procedure with decrease over subsequent weeks. These data may suggest that the optimal time of membrane bioactivity is earlier than suspected. Samples of human induced membrane tissue were assayed for multiple time points. One-month-old membrane samples had the highest expression of VEGF, IL-6, and Col-1, whereas two-month-old membranes expressed <40% of the levels of the one-month-old membranes [26]. This study suggests a time-dependent decrease in bioactivity of the membrane and may suggest a role for earlier secondary grafting. So in the absence of definitive evidence for specific timing, grafting can be safely performed as soon as the wounds have healed well without evidence of residual infection and systemic antibiotic therapy is near complete (4–6 weeks). There is likely little benefit to protracted delays (greater than 8 weeks) to secondary graft application.

15.4 Cage Technique

In 2002, Ostermann published the first reports of extending the indication for use of titanium mesh cages to restore bony continuity [27]. These devices are routinely utilized in spine surgery to augment the use of nonstructural allograft. They have demonstrated adequate ability to achieve bony union in conjunction with bone graft [28, 29]. The goal of utilizing the titanium cage is that cancellous allograft and demineralized bone matrix products offer advantages of no donor-site morbidity and ease of application. The difficulty in utilization of nonstructural allograft bone is that it does not reliably lead to bony union in gaps greater than 3 cm, those of critical cortical defects. The addition of the titanium mesh cage extends the application of the allograft material by imparting additional stability.

The technique involves either plate or intramedullary nail stabilization. It can be performed either acutely, on a delayed basis or in a nonunion setting. In each case, the cage is premeasured in accordance with the diameter of the bone and also the length of the defect to be spanned. The cage is prepared with a packing that consists of cancellous bone graft, and if an intramedullary nail is to be used, the guide wire is passed through the middle to ensure that there is no mechanical blockade to passage. Standard intramedullary nailing techniques can then be utilized including reaming over a guide wire (Fig. 15.7). Ostermann, Attias, and Cobos all reported success in small series with minimal complication, most notably in leg length discrepancy [27, 30–32].

In some situations, plate osteosynthesis might be the preferred method. Attias recommended plate osteosynthesis in the setting of nerve exploration or when intramedullary nailing might be suboptimal such as a proximal or distal metaphyseal segments. The same methodology of preparation was performed in the single case report using this method, and the cage was implanted and compressed into the bone ends of a humeral fracture associated with a gunshot wound. They suggested the use of orthogonal plating to impart greater stability and allow for early motion [30].

15.5 Metal Tantalum for Defects

The use of metal alloys for structural substitution is an atypical technique and reserved for situations where regeneration is unfeasible, unlikely, or the patient declines other techniques. Any of these applications would certainly be considered “off-label” techniques since none of the currently available tantalum devices are intended for trauma applications.

15.5.1 Material

Tantalum is a transition metal (atomic number 73; atomic weight 180.05) that remains relatively inert in vivo. Porous tantalum is an open-cell tantalum structure of repeating dodecahedrons with an appearance similar to cancellous bone has been developed for clinical applications. (Zimmer-Biomet, Trabecular Metal Technology, Inc., Parsippany, NJ, USA). The basic structure of this porous tantalum metal yields a high volumetric porosity, a low modulus of elasticity, and relatively high frictional characteristics [33]. This frictional characteristic makes immediate stable interfaces with bone feasible and allows the potential for early or immediate weight bearing (Fig. 15.8) [34].

Porous tantalum structures utilized for orthopedic implants have a porosity of 75–85% compared to CoCr sintered beads (30–35%) [35]. The rigidity of porous tantalum increases with decreasing porosity. Current tantalum implants maintain a rigidity similar to the human fibula [36]. These characteristics optimize the biocompatibility of these implants.

In addition to its high biocompatibility, the frictional characteristics and the rigidity similarity to native bone make porous tantalum an intriguing candidate for defect management. With tantalum implants in structural defects, stable implantation, structural support, and limited local stress shielding are feasible.

15.5.2 Bone Ingrowth Potential

The porosity of current tantalum implants has been designed to optimize bone ingrowth potential [37]. A recent in vivo study sought to evaluate the interaction between human osteoblasts and porous tantalum and convincingly demonstrated that porous tantalum is a good substrate for the attachment, growth, and differentiated function of human osteoblasts.

The current tantalum implants used for defects are designed for bone defect management around joint replacements. While not primarily designed for trauma, many of the shapes have been

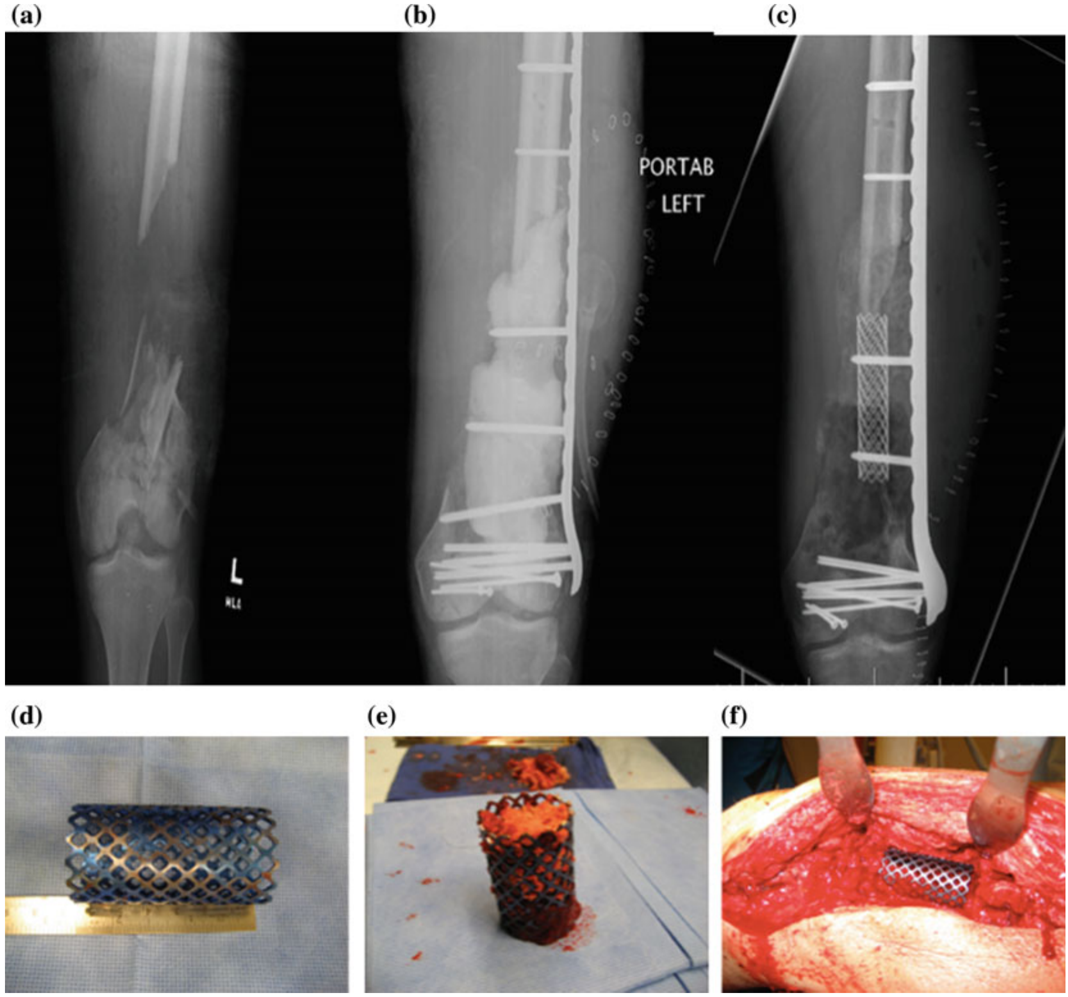

Fig. 15.7 31-year-old male motorcyclist who suffered complex intraarticular distal femur fracture with extensive bone loss. **a**–**c** Patient underwent initial Masquelet technique after extensive debridement and bone grafting was assisted by the integration of a titanium mesh cage supported by screw fixation through the plate and massive autologous and allogeneic bone graft. **d**–**f** The cage, demonstration of packing the cage with bone graft, and a clinical photograph demonstrate the technique. (The cage images courtesy of Brian J. Cross, DO, Broward Health Medical Center, Plantation FL, USA)

adaptable to the shape of common diaphyseal and meta-diaphyseal defects (Fig. 15.9).

15.5.3 Applications

Tantalum can be used for reconstruction of diaphyseal defects of large size. Our experience has been primarily in knee arthrodesis in conjunction with an intramedullary device for stabilization. This size defect will require multiple implants used end to end but allows for full defect reconstruction and immediate weight bearing (Fig. 15.10).

Metaphyseal. We have used tantalum most frequently in the setting of metaphyseal bone loss—for both complete and incomplete defects. Metaphyseal reconstructions can be done with either a plate of an intramedullary device for stabilization. Defects can be modified to accept

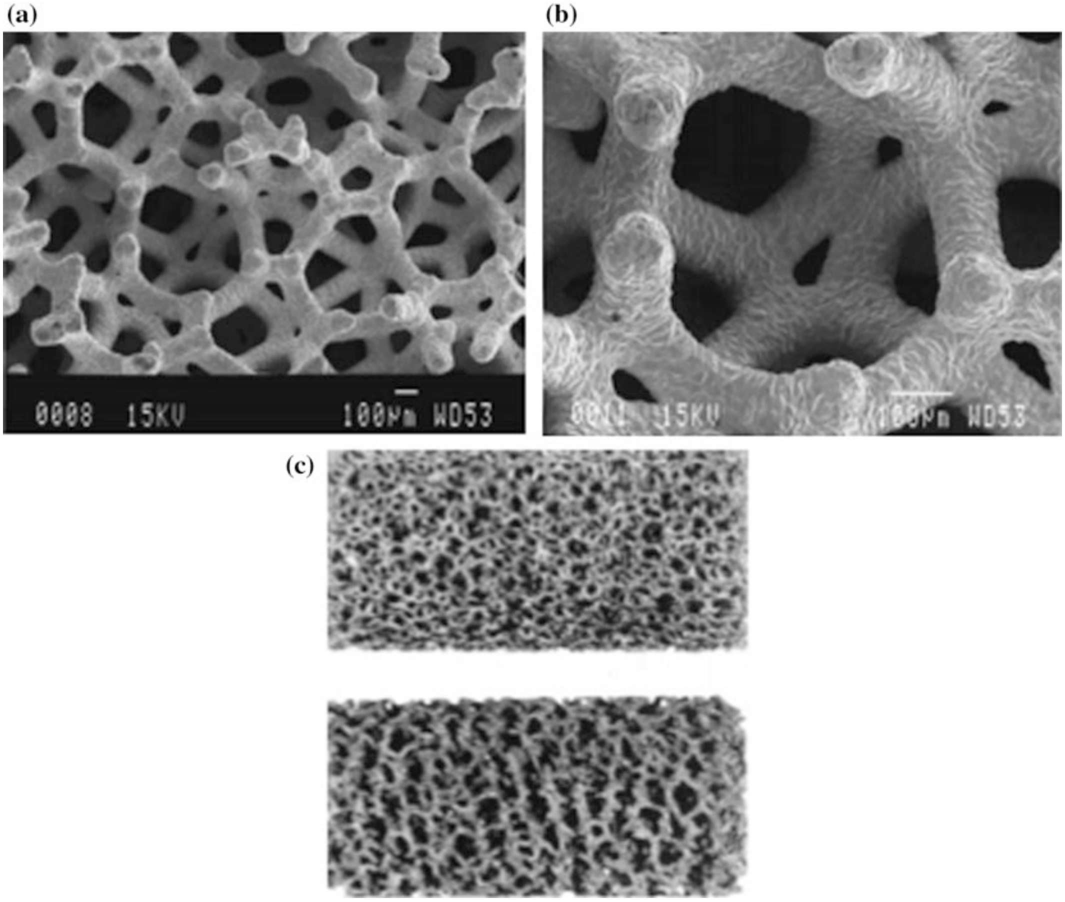

Fig. 15.8 **a** Scanning electron micrograph of porous tantalum showing the cellular structure formed by the tantalum struts. There is the occasional smaller opening or portal that interconnects with the larger pores or cells. **b** Higher power scanning electron micrograph of a single pore illustrating the surface microtexture on the struts caused by crystal growth during the process of tantalum deposition. **c** Photographs showing transcortical implants with small and large pore sizes (From Bobyn et al. [34] with permission of The British Editorial Society of Bone & Joint Surgery)

the flat ends of the implant, and load can be applied. The most common indication for tantalum is critical size bone defect in patients who have declined traditional approaches to bone regeneration (bulk grafting or distraction osteogenesis), patients who cannot comply with limited weight bearing postsurgically, and patients with poor bone regeneration potential (elderly, systemically ill). *Patients must be informed that this is an off-label application.*

Outcomes. There are no published outcomes of using tantalum for defect reconstruction. There are ongoing concerns about risk of infection with the use of tantalum in traumatic wounds and the required resection in the setting of a fulminant infection. However, in theory, this approach is not significantly different than the currently utilized induced membrane technique, which utilizes a PMMA spacer. If an infection were to occur, there is likely formation of a

Fig. 15.9 Multiple different tantalum implants that can be fashioned for critical bone loss substitution

vascularized scar response around the implant that could ultimately be grafted.

15.6 Tissue Transfer

Except for distraction osteogenesis, the other techniques described above involve the use of bulk bone grafting that provides an avascular healing zone that requires creeping substitution with cells migrating from the intact bone through the matrix. The risk of nonunion, fracture of the transplanted bone, and overall poor microarchitecture of the healed environment places the patient at high risk. This can be obviated by distraction osteogenesis or vascularized tissue/bone transfer. The maintenance of periosteal and endosteal blood supply allows for healing and remodeling through both the vascular pedicle and the local supporting vasculature with osteoblast induction.

Fibula. The vascularized fibula (pedicled or free) is the most well-studied of all vascularized bone grafts in long bone loss. The fibula as a bony anatomic unit is quite versatile as it is similar to the radius and ulna in shape and size, can be used intramedullary in the humerus and can even be medialized to substitute for the tibia. The vascular supply is from the peroneal artery and veins, which provide a dual endosteal and periosteal supply from both the nutrient artery and the musculo-periosteal vessels [38]. It can be utilized as a purely osseous, or with the overlying skin and muscle depending on the amount of type of bone and soft tissue loss associated with the injury. One of the disadvantages of utilization of the vascularized fibula is the small caliber of the bone, which can be compensated for with the double barrel technique that allows for the long fibula donor (which can be a maximum of 26 cm in length). Modifications such as this allow for broad application of the graft with the only limitation being the technical nature of the surgical harvest and implantation requiring a skilled microvascular surgeon [38, 39]. Outcomes of use of the vascularized fibula in the upper extremity demonstrate excellent incorporation at 3 months. In the lower extremity the fibula can be applied to the foot and ankle in standard fashion if there is an adequate location for anastomosis outside the zone of injury, but in the tibia different techniques might be used (Fig. 15.11). Medialization of the fibula to substitute for segmental bone loss can be performed primarily or with Ilizarov techniques, but must at all times account for the condition of the soft tissues [40].

Rib. Defects of the clavicle are rare but difficult to heal lesions that can be associated with longstanding nonunions. They occur in patients who often have had multiple failed procedures and there is no single answer to the reconstruction of these defects. Traditionally tricortical iliac crest with compression has been the standard of care with variable success rates. The advantage of this technique is the relative simplicity and ability to reconstructs small defects to equalize the affected clavicle to the length of the contralateral side. Larger defects may benefit from both a vascularized bone graft and compression. A free pedicled transfer is less than ideal in this region of the body. Free transfer of a vascularized rib pedicle has been utilized for mandibular, maxillary and extremity defects (tibial, calcaneal and humeral) [41]. This graft has also been studied in a rotational manner for the clavicle where a serratus anterior flap is taken with the seventh and eighth rib and tunneled under the pectoral musculature then embedded into the debrided clavicle with compression fixation. This is done in a double barreled fashion that allows for adequate strength [42]. In a few case studies this has demonstrated long term success and although technically challenging this

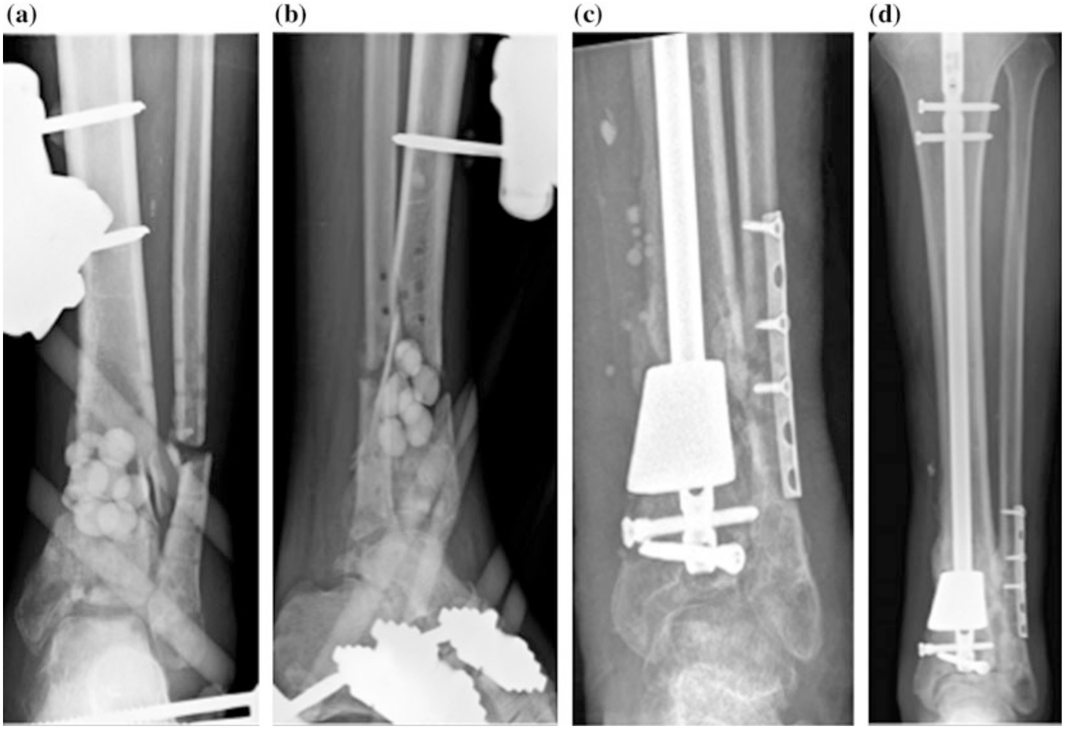

Fig. 15.10 This patient had purulent infection after ORIF distal tibia fracture with articular extension. **a, b** He underwent radical resection of infection and had antibiotic beads placed after moderate bone resection was required. **c** After 6 weeks of intravenous antibiotics and replacement of beads with a solid spacer, he had removal of his antibiotic spacer, placement of an intramedullary nail through a tantalum spacer, and autogenous cancellous grafting. **d** At 5 months, he is free of infection with full incorporation of tantalum implant

technique can provide both mechanical and biologic advantages for the patient.

Medial Femoral Condyle. The medial femoral condyle has been extensively studied for small defects as it is taken as a cortico-periosteal graft that is supplied by the descending genicular artery. Traditionally this was described as a thin, non-biomechanically strong graft that is easily isolated and transferred into a site of defect with cancellous bone harvested most commonly from the iliac crest. The harvest site is highly reliable and it provides an answer for small areas of necrotic or missing bone (Fig. 15.12). The average size of flap is 5 cm in length; however; recent studies have demonstrated the potential harvest site to be as much as 13 cm [43, 44].

Other sources of vascularized bone transport will likely be identified in the future. There have been limited reports of others including a vascularized pelvic flap for calcaneal substitution [45]. These reports are limited case series or single case reports, but all identify the value of a vascularized graft particularly in the post-radiation, recalcitrant nonunions, and necrotic bone loss patients.

15.7 Summary

Nonunion care requires significant thought and precision with respect to achieving a sterile zone of injury along with an adequate understanding of the causative factor in a failure of bony regeneration. The occurrence of bone loss is not at all uncommon with respect to nonunion, and when critical cortical defects occur beyond 4 cm, special techniques must be employed to achieve complete reconstruction and return to function for patients.

For massive defects, especially in the setting of current or prior infection, distraction

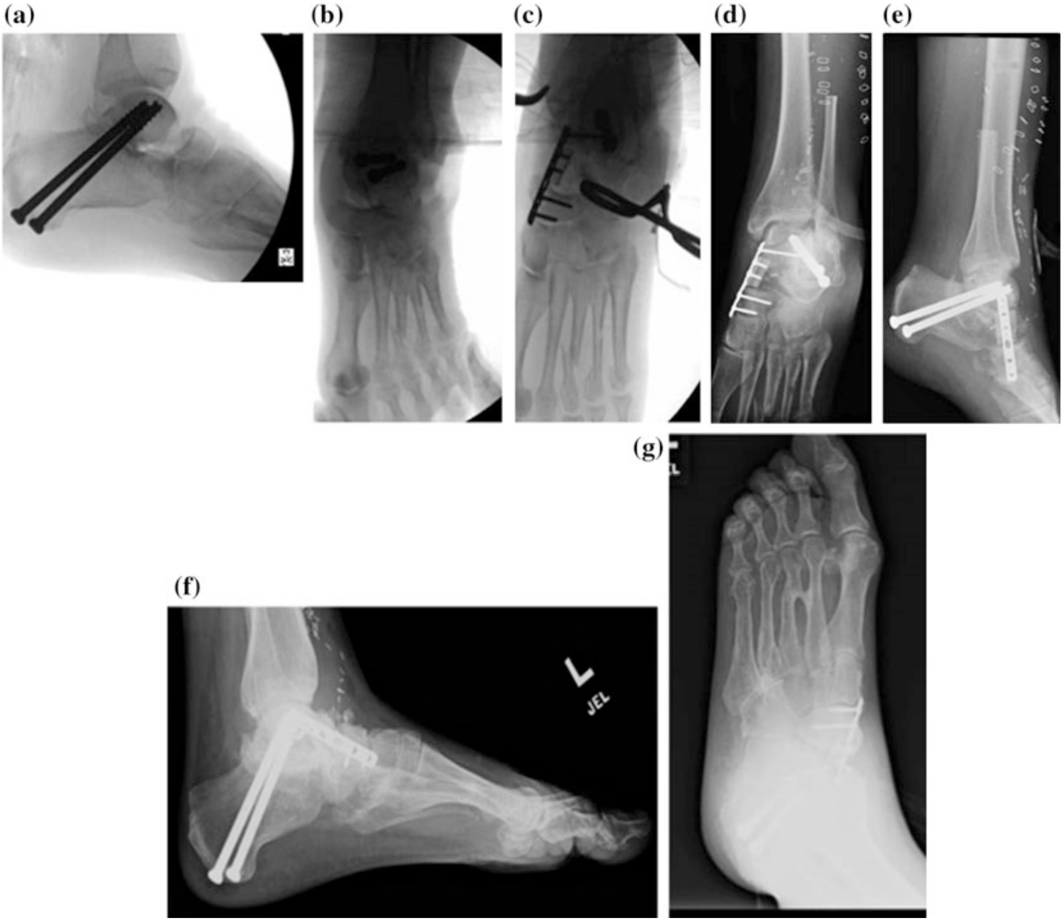

Fig. 15.11 55-year-old female injured in a fall from a burning building, with a complex open fracture dislocation of the hindfoot. Complete traumatic loss of the talar head at the talonavicular joint. **a–e** Primary subtalar arthrodesis performed along with vascularized free fibula transfer to achieve both soft tissue coverage and a talonavicular arthrodesis. **f–g** Radiographs at 1.5 years demonstrate bony healing with a nonantalgic gait and complete return to function

osteogenesis remains as the technique of choice for regeneration.

For large diaphyseal or metaphyseal defects, especially with no evidence of infection and stable fixation constructs, an induced membrane technique with cancellous grafting can be safely utilized. Metal cages can be used during reconstruction to contain the cancellous graft, provide stability benefit, and potentially improve graft efficiency.

More unique approaches can be utilized in more challenging cases. Metal substitution is an alternative when patients decline other approaches to critical size defects or cannot comply with weight bearing limitations. Vascularized bone transfer is an alternative at centers that have microvascular expertise and in settings where the local blood supply will likely not support vigorous osteogenesis.

BMP with allograft cancellous chips remains an alternative for small to medium size defects, especially in the setting of a diaphyseal defect treated with an intramedullary rod. However, the quality of bone regenerate created by this approach and potential local inflammatory consequences limit the use of BMPs as a first-line approach.

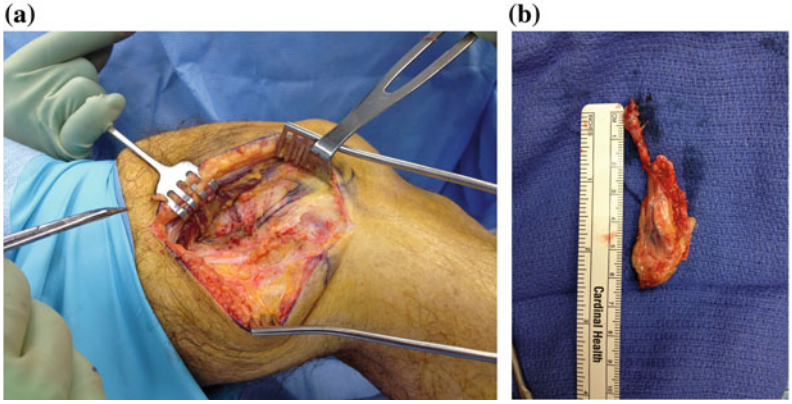

Fig. 15.12 The medial femoral condyle-free vascularized graft is ideal for small areas of necrotic bone. The harvest site is easily identifiable (**a**) and yields a graft that can be interposed into areas of bony loss (**b**), particularly useful in the distal aspects of the extremities. (Image courtesy of John S. Reach, Jr., MSc, MD, Yale University School of Medicine, New Haven CT, USA)

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