Clinical Imaging 67 (2020) 15–29

Contents lists available at ScienceDirect

Clinical Imaging

journal homepage: www.elsevier.com/locate/clinimag

Musculoskeletal and Emergency Imaging

Radiographic evaluation of reconstructive surgery for segmental bone defects: What the radiologist should know about distraction osteogenesis and bone grafting

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ARTICLE INFO

Keywords:
Bone transport
Distraction osteogenesis
Bone grafting
Trauma

ABSTRACT

Radiologists work in conjunction with orthopedic surgeons to evaluate the progression of bone healing and identify potential problems during bone reconstruction. Accurate evaluation and identification of healing progression or complications are critical to optimizing successful patient outcomes with either distraction osteogenesis or bone grafting. Therefore, radiologists must understand the fundamental concepts behind these surgical reconstructive techniques in order to provide accurate postoperative radiographic assessments. The cases and discussion within this review aim to provide this foundational knowledge.

1. Introduction

There are two predominant mechanisms by which fractures heal. Primary (direct) bone healing occurs when orthopedic fracture fixation is applied to achieve absolute stability resulting in healing through direct Haversian remodeling and gap remodeling. Secondary (indirect) bone healing results from relative stability and involves formation of callus and healing through endochondral ossification [1]. However, bone defects secondary to trauma, infection, malignancy, and congenital deformity are sometimes too large to allow for either of these pathways to progress to healing without additional intervention.

There are many surgical techniques that address bone defects, and each technique results in different postoperative radiologic findings. Commonly used techniques include distraction osteogenesis with external or internal fixation devices, and bone grafting with autograft, allograft, or synthetic substitutes. Radiologists must understand bone healing mechanisms, recognize surgical fixation techniques utilized in reconstructing large bone defects, comprehend the image findings associated with the different types of bone healing, and recognize potential complications. Herein we summarize the literature of a variety of commonly used reconstructive techniques and present radiographic evaluation of these cases.

1.1. Radiographic evaluation of distraction osteogenesis

Distraction osteogenesis (DO) refers to the process of forming new bone at the site of a corticotomy/osteotomy undergoing controlled distraction. This technique can be used to treat bone defects or limb length inequalities (also termed limb lengthening). When distraction osteogenesis is used to address bone loss (as opposed to lengthening a bone) it is titled bone transport [2]. This process involves performing a corticotomy/osteotomy at an area of healthy bone at one end of a bone defect thereby creating a bone segment that can be slowly transported across the length of the defect. The new bone that forms is termed “regenerate”, and it is unique in that it typically forms through intramembranous ossification [3,4].

The success of DO relies on sequential radiographic evaluation. The main tool to assess for successful healing of DO is radiography. Radiographic follow up is a critical component in using this technique and is essential to guide decisions such as removal of external fixators and altering the rate of distraction. The presence of three healed

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https://doi.org/10.1016/j.clinimag.2020.05.018
Received 23 March 2020; Accepted 18 May 2020

Table 1
Diameter of callus formation. Percentage calculated using the averaged measurement of AP + lateral radiographs. Adapted from Tirawanish et al.

Percent Diameter (%)	Score
< 20	1
21–40	2
41–60	3
61–80	4
81–100	5

cortices on anteroposterior and lateral radiographs is commonly used as an endpoint for healing [5,6]. Though useful, this method is fraught with difficulty in achieving agreement between practitioners, with reported interobserver rates of < 0.5 [7].

Radiographic classifications have been proposed to help standardize our description of regenerate bone [8]. As described by Li et al., the radiographic features can also be summarized by regenerate shape and type [9]. The shape is based on a comparison of the regenerated bone to the corticotomy site and can be classified as fusiform (regenerate wider than original bone), cylindrical (regenerate and original bone of the same width), concave (regenerate is narrower than the original bone with central attenuation), lateral (regenerate mainly on one side of the gap), and central (thin regenerate in the central portion). The density of the regenerate relative to adjacent tissues cortex is also described and shown to be an important component in describing regenerate to predict outcomes. Patterns are described as sparse, homogenous, heterogeneous, and lucent, with three possible bone densities (low, intermediate, normal).

Although a complete description of all regenerate types is out of the scope of this article, it is important to recognize patterns that could potentially predict a poor outcome. Having a homogeneous regenerate is associated with a favorable healing index (< 80 days/cm) regardless of density [9]. In contrast, having a heterogenous regenerate pattern is associated with prolonged healing index (> 80 days/cm) [9]. Heterogenous patterns can thus alert practitioners to potential problems, and may indicate mechanical instability (inappropriate fixation), or too fast a distraction rate. Lucent areas within the regenerate may represent cysts and can indicate deficient bone formation in that area. A homogenous regenerate is thus the ideal pattern. The pixel density ratio has also been studied as a more objective measure of bone healing [8]. Although an absolute value does not exist, relative ratios can provide an objective measurement of callus quality. Measuring pixel density in cortical and medullary regions was shown to correlate favorably with bone mineral density [8].

A simpler scoring system can also be employed to help guide practitioners in making clinical decisions (Tables 1,2) [10]. A diameter score of 5 (> 80%) was shown to significantly prevent callus subsidence. Callus diameter of 41–60% (similar to three cortices on x-ray) may be insufficient to prevent physiologic loads.

1.2. *Technical aspects of distraction osteogenesis*

DO can be performed using external fixation, internal fixation, or a combination of devices because bone regeneration follows the transported segment until it "docks" at the far end of the defect. The bone segment is transported with a cable, wire, or half pins attached to a circular external fixator [11]. Rate and rhythm of the transport is a critical aspect to achieving high quality regenerate. Most often the distraction is performed at a rate of 1 mm per day (Fig. 1) [12–14]. For certain injuries, surgeons may perform more than one osteotomy, thereby creating two or more mobile bone segments that can be transported concurrently in tandem or in converging directions to expedite bone regeneration in the defect (Fig. 8) [15].

It is important for the radiologist to understand concepts behind the three phases of distraction osteogenesis in order to appropriately interpret postoperative radiographs [16]. The first phase is referred to as the latency period, which is the time after the osteotomy is performed but before the segment has begun transport. This latency period typically ranges from 3 to 10 days and is meant to allow time for the induction of an inflammatory response and formation of early callus [16,17]. During this phase, neovascularization of bone at the corticotomy site occurs and early callus forms but is often still difficult to visualize.

The second phase is distraction, during which the mobile bone segment is pulled through the length of the defect. Distraction of the callus by the transported bone segment results in the formation of a column of trailing regenerate bone. The regenerate bone is first seen radiographically between 3 and 6 weeks following the start of the distraction phase (Fig. 1E) [16]. Absence of calcification of the regenerate by the end of this timeframe is potentially concerning for poor regenerate formation and may require alterations in treatment strategy. After a good initial regenerate is noted, the distraction phase continues until the transported bone segment reaches the docking site at the far end. During distraction, it is important to monitor for the shape of the regenerate column. A regenerate column that takes on an

Table 2
Density score based on regenerate quality. Adapted from Tirawanish et al.

Density	Characteristic	Score
Low	Heterogeneous bone (density similar to adjacent soft tissues)	1
Low-intermediate	Heterogenous bone (density similar but lower than adjacent cortex)	2
Intermediate	Heterogenous bone with multiple cysts or saw-tooth lines (density similar but lower than adjacent cortex)	3
High	Normal bone density	4

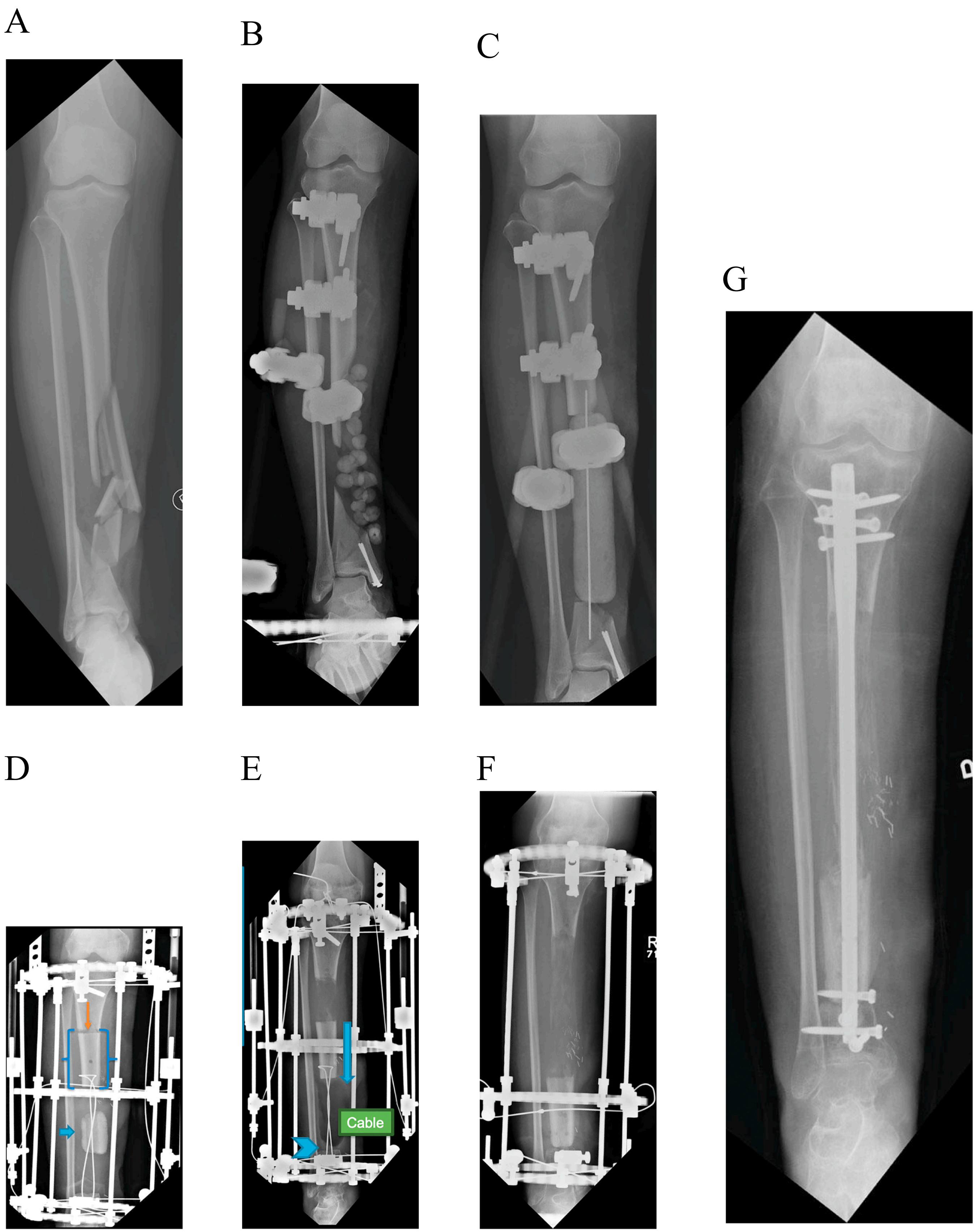

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Fig. 1. A: 19-year-old female in motor vehicle accident Initial injury radiograph demonstrating highly comminuted, multi-segmented fracture of the mid tibial diaphysis extending to the distal tibial diaphysis with fracture lines extending into the ankle. B: Initial stage of debridement with placement of external fixator and antibiotic impregnated cement beads. C: Further debridement and temporary filling of large segmental defect with antibiotic cement spacer held in place with a Kirschner wire. D: Cable transport for distraction osteogenesis. E: Radiograph 8 weeks post-op, 7 weeks into distraction phase. Advancement of rods and cable to achieve 4 cm interval lengthening. Long blue arrow demonstrates direction of transport. Blue arrowhead indicates eventual docking site of the mobile bone segment at the distal end of the segmental defect. F: Radiograph 5 months post-op demonstrating removal of cable system with a wire placed in the transport segment to maintain its position while soft tissues heal over docking site. Immature regenerate will bridge the 16 cm gap. G: Placement of antibiotic cement coated intramedullary nail.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

hour-glass appearance that is thinning in the middle may be a sign that distraction is occurring too quickly. A regenerate column that appears of equal width to the transport segment without indentation indicates good formation and an appropriate rate. A regenerate column that is wider than the transport segment is not necessarily unfavorable but should be noted as a possible sign that transport is progressing too slowly and could become at risk of premature consolidation.

The third and final phase is consolidation, which describes the process that occurs following bone transport during which mineralization, remodeling, and maturation of the regenerate bone occurs (Fig. 1F). This phase may require an estimated 1 to 1.5 months per centimeter of new bone formation and is roughly twice as long as the distraction phase [12,16,18]. Overall, the timeframe for reconstruction using classical methods is quite long with an average of 15 to 18 months for a 10 cm segmental bone defect [19].

As the mobile bone segment is transported through the length of the defect, it will eventually reach its final destination at the opposite end of the defect, often referred to as the docking site (Fig. 1E). The consolidation phase will continue while the transport segment is compressed at the docking site. Healing at the docking site continues during consolidation of the regenerate until sufficient callus formation, mineralization, and remodeling have occurred to achieve complete healing (Fig. 1F) [20]. It is notable that during the time it takes to complete the transport phase, the distal end of the segmental defect may generate fibrocartilage and soft tissue can subsequently collapse into the space created by the bone void with both acting as physical barriers to docking site union [12]. This may require an additional procedure in order to remove these tissues and allow for docking with bone-on-bone contact. It is important for the radiologist to recognize radiographic union between the transport segment and the docking site, as delayed union or nonunion may require bone grafting or additional fixation (Fig. 1G) [12].

DO can be accomplished with a number of different external fixation constructs. The most classic is a traditional Ilizarov external fixator, which has stainless steel or carbon fiber rings connected by threaded rods as a scaffold upon which fixation points are applied to manipulate the bone fragments. A hexapod external fixator, such as the Taylor Spatial Frame, is also a circular fixator, but in this construct the rings are connected by six struts. The struts are adjustable and allow for angular and translational correction of alignment in six planes. Another construct is the monolateral rail located on one side of the bone and thus rely on Schanz pins with no option for high-tension wires. These devices are less bulky and cumbersome for the patient, especially in the thigh, but are mechanically inferior and may lead to deformity as distraction progresses due to the cantilever forces on the device. This is relevant as recognizing a drift into varus alignment with femur distraction or valgus and apex anterior deformity with the tibia distraction is critical so that it can be corrected prior to healing.

Although it is helpful for the radiologist to recognize the type of frame being used when evaluating a postoperative radiograph, the concepts behind distraction osteogenesis do not differ between surgical techniques. Regardless of the technique, the essentials for postoperative radiographic monitoring include distance traveled by the transport segment, callus formation, regenerate formation, mineralization, and docking site union. Complications that can be recognized radiographically include poor regenerate formation, premature consolidation before transport is complete, malalignment of the overall bone axis, deformity of the transport segment, progressive deformity during distraction, hardware breakage, pin site infection and loosening, docking site nonunion, poor regenerate healing from fixator instability, deep infection with osteomyelitis, and re-fracture of newly formed bone [21,22].

1.3. Bone grafting

In addition to distraction osteogenesis, bone grafting can be utilized to address bone defects. The types of bone grafting available include autograft, allograft, and bone substitutes; the decision of which type to use is often based on the size and location of the defect. The ability for any graft to promote bone healing relies on three main qualities: (1) osteogenesis, the presence of osteoblastic cells or osteoblastic precursor cells that are capable of forming new bone; (2) osteoconduction, the ability of the graft to serve as a scaffold onto which new bone can grow; and [23] osteoinduction, the ability to induces differentiation of osteoprogenitor cells into osteoblasts [22,24,25].

1.4. Autograft

Bone autograft is bone that is transported from another part of the recipient's body and re-purposed, often to fill a defect in the setting of trauma or tumor. Bone autograft is most commonly used for segmental defects < 5 cm and is most often sourced from either the patient's own iliac crest, the current gold standard harvest site, or through harvesting of the femur using a reamer-irrigator-aspirator (RIA) [26,27]. The size of the defect dictates which autograft can be used, whether it be iliac crest bone graft for smaller defects or a fibular shaft autograft for defects up to 30 cm [28]. Disadvantages of autografts include donor site morbidity, increased surgical time, blood loss, and insufficient amount of bone graft harvested with the use of iliac crest or RIA [29].

While the gold standard for bone autograft harvest has been the iliac crest, recent studies have shown that RIA may reduce harvest site morbidity and produce larger volumes of graft compared to iliac crest

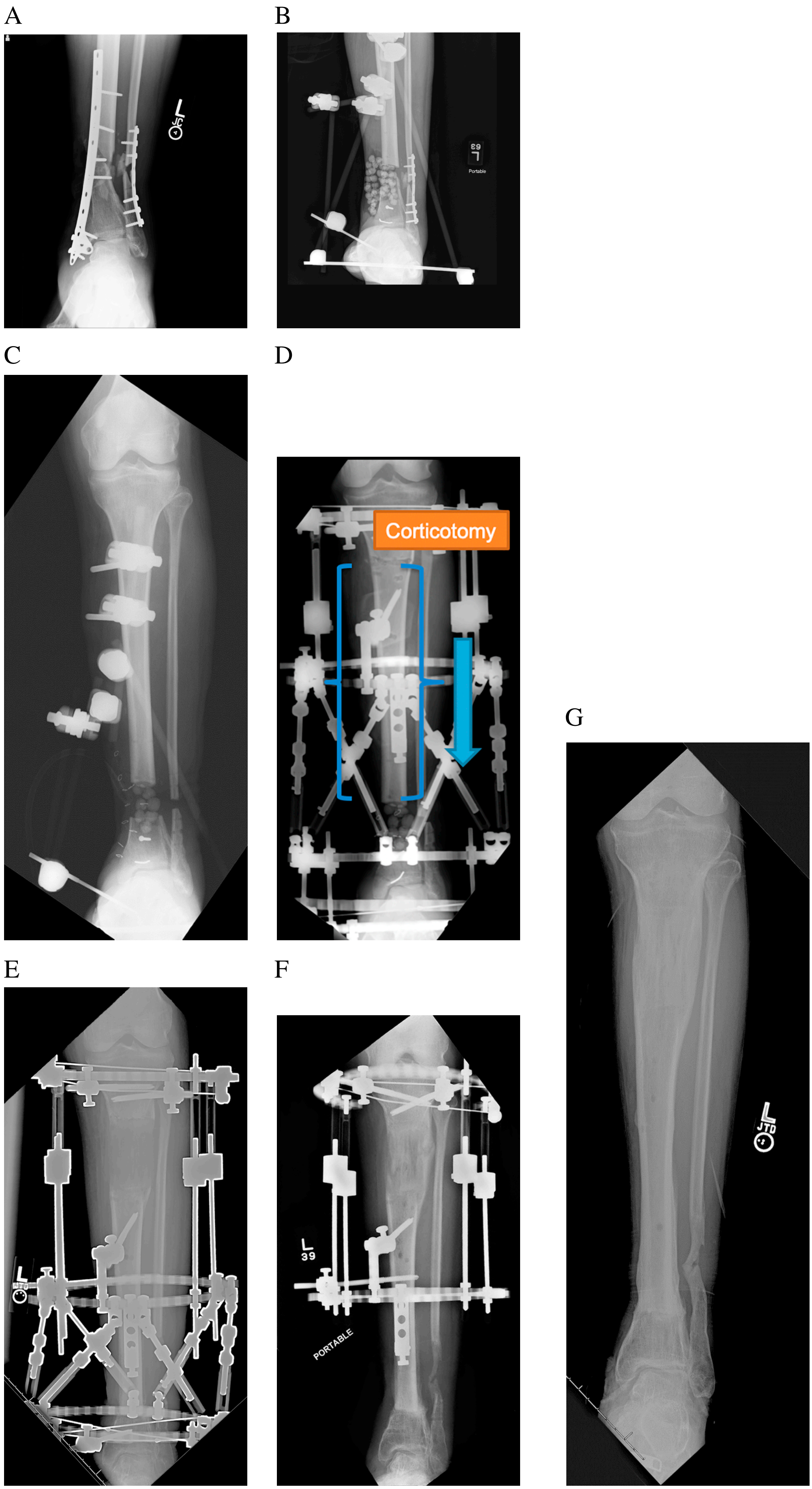

Fig. 2. A: 62-year-old man who sustained open left distal tibia and fibula fractures from motor vehicle collision presenting 7 months after injury with 8 cm medial soft tissue defect, exposed bone and hardware, and purulent drainage. B: Stage One: initial removal of tibial plate and screws, debridement, placement of an external fixation device, joint reduction and limited fixation with pins, and antibiotic beads. C: Stage Two: further debridement, removal of the fibular plate and soft tissue closure with intentional shortening and deformity. D: Corticotomy site made in proximal healthy bone (blue arrow indicates the direction of the transport and blue brackets indicate the bone transport segment). The external fixation construct is considered a bifocal transport frame with telescopic rods proximally and Taylor Spatial Frame hexapod struts distally. There is also a foot ring attached distally with wire fixation in the foot and no fixation present in the distal articular bone block. E: Radiograph 6 months after initial osteotomy with docking of the bone transport segment into the distal fracture segment and interval removal of antibiotic beads. Also note that the foot ring has been removed and a combination of tensioned wires and a sagittal plane Schanz pin had been added to the distal articular bone block. F: Radiograph showing interval removal of the distal frame and a healed docking site 10 months after surgery. There is increased mineralization and consolidation at the site of distraction osteogenesis. G: Radiograph 29 months after surgery with notable maturation of bone healing and significant remodeling. Also note the recreation of normal bone anatomy with neocortex and intramedullary canal formation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

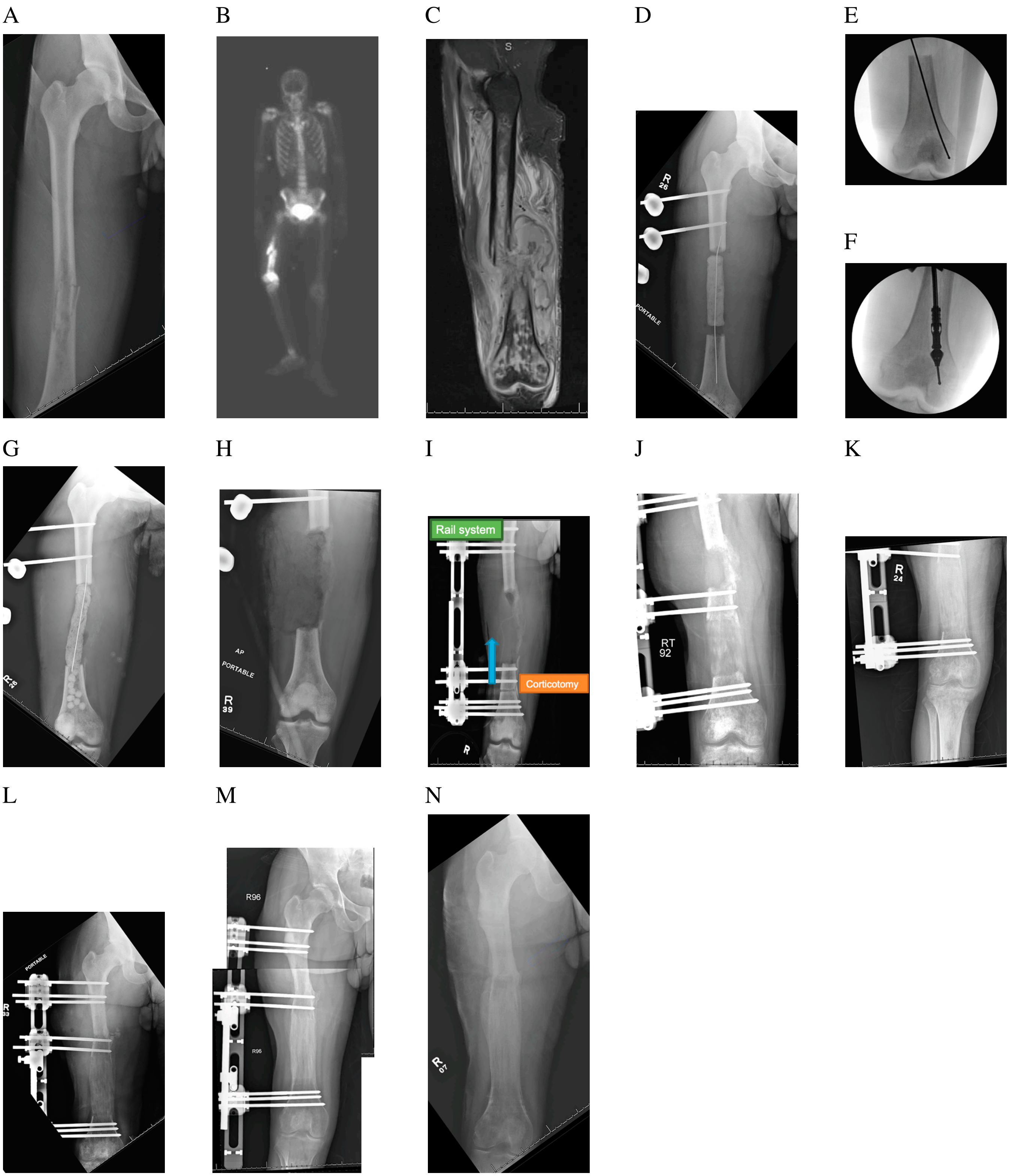

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Fig. 3. A: 30-year-old man who sustained a right diaphyseal midshaft femur fracture through a permeative lucent lesion following a fall from standing. B: Bone scan demonstrating diffusely increased uptake in all phases involving the right mid to distal femur around the pathologic fracture. C: MRI demonstrating increased signal intensity within the bone and surrounding soft tissue consistent with osteomyelitis and a large abscess. D: Spanning unilateral external fixation, resection of infected and devascularized cortical bone segments and placement of an antibiotic impregnated polymethylmethacrylate cement spacer to temporarily fill the large defect, sterilize the environment, and create an environment optimally conducive to bone transport. E: Ball-tipped guidewire passing through the intramedullary canal into the femoral condyles. F: Ball-tipped guidewire passing through the intramedullary canal into the femoral condyles. G: Antibiotic beads were placed in distal femur after cement spacer was exchanged due to purulent material. H: The following week, antibiotic beads and spacer were removed leaving a 13 cm defect. I: Distal corticotomy was made and a monolateral rail lengthening system (Modular Rail System) was applied for bone transport. J: 3 months post-op showing robust distal regenerate. There is also notable heterotopic bone that has formed in the transport gap. K: 5 months post-op and is now clear that the intervening heterotopic bone will prevent docking of the bone segments without intervention. The distal regenerate is healing well with excellent calcification. L: 7 months post-op lengthening. M: 18 months post-op lengthening with healed docking site while still in fixator. N: 19 months post-op lengthening showing appearance of a healed docking site and fully consolidated regenerate at the final follow-up after fixator removal.

bone graft with non-inferior osteoinductive and osteogenic properties [24,30].

1.5. Allograft

Bone allograft is bone that is obtained from a donor and subsequently transplanted into a recipient. Allografts are often harvested from the ribs, femur, tibia, and fibula for use in reconstruction of joints or long bones and limb salvage [25]. Advantages of allograft use is that there is no donor site morbidity or complications associated with harvest and that the needed quantity is readily available. Disadvantages to using allograft as opposed to autograft include delayed vascular penetration, slow bone formation, accelerated bone resorption, extrusion, infection, and a higher incidence of nonunion [29,31]. Overall, these allografts can be used for structural support and provide a good alternative to using autograft.

1.6. Bone substitutes

Bone graft substitutes include bone bank allograft, demineralized bone matrix (DBM), osteoconductive materials, and osteoinductive proteins that can either replace autograft or supplement autograft. Demineralized bone matrix (DBM) and bone morphogenic protein are types of bone allograft substitute with osteoinductive properties that provide volume expansion and bone graft enhancement [27]. While DBM does not provide structural support like a fibular autograft or allograft, it is able to fill small bone defects, cysts and cavities [25].

1.7. Radiographic evaluation

Overall, just as it is important for radiologists to understand the surgical technique and concepts behind DO, it is equally important to understand the concepts behind bone grafting to accurately assess postoperative (post-op) healing and recognize potential complications. Though auto or allografts offer an alternative to distraction osteogenesis for larger bone defects (Figs. 5 and 6) [28], radiographic evaluation of these grafts requires monitoring for graft incorporation, as well as the potential complication of fracture [32,33]. Furthermore, because bone grafting undergoes a different mechanism for incorporation (creeping substitution), as opposed to a more “natural” intramembranous ossification, this tends to form a “bar” rather than the more physiologic cortex-canal seen in distraction osteogenesis. Finally, radiographically speaking, bone grafts demonstrate the highest level of opacity in the early postoperative period and become more lucent with time as the graft begins to resorb or incorporate (Fig. 7) [31].

2. Cases

2.1. Case 1

19-year-old woman ejected passenger from a motor vehicle resulting in an open, highly comminuted, multi-segmented fracture of the mid tibial diaphysis extending to the distal tibial diaphysis with fracture lines extending into the ankle. Fig. 1A is the initial injury radiograph. This injury required debridement and multi-stage reconstruction due to the open and multi-fragmented fracture that was both highly contaminated and with segmental bone loss. The size of the segmental bone loss combined with the high risk wound made distraction osteogenesis the preferred technique. Fig. 1B demonstrates the initial stage of debridement, placement of an external fixator, and placement of antibiotic impregnated methylmethacrylate cement beads. Fig. 1C is a postoperative image from the second stage surgery, which involved further debridement and temporary filling of the large segmental defect with an antibiotic cement spacer held in place with a Kirschner wire.

For functional use of the limb, salvage was pursued utilizing distraction osteogenesis via a cable transport technique (Fig. 1D) [34]. The transport segment is designated by the blue brackets. The osteotomy was performed in a location of healthy bone proximal to the defect (orange arrow).

An antibiotic cement cannulated spacer (blue arrow) was placed in the bone gap to help maintain the soft tissues open for transport. Fig. 1E is an x-ray taken 8 weeks postoperatively, roughly 7 weeks into the distraction phase. This demonstrates advancement of rods and cable to achieve 4 cm interval lengthening and demonstrates regenerate formation proximal to the mobile bone segment with an appropriate shape and level of calcification. The long blue arrow demonstrates the direction of transport. There is interval removal of the antibiotic cement spacer. The blue arrowhead indicates the eventual docking site of the mobile bone segment at the distal end of the segmental defect.

Fig. 1F was taken 5 months postoperatively. Once the transport segment reached its final destination at the docking site, the cable system was removed. A wire was temporarily placed in the transport segment to maintain its position while the soft tissues healed over the docking site. Immature regenerate bridges the 16 cm gap. An antibiotic cement coated intramedullary nail was placed after 2 weeks allowing for 2 weeks of soft tissue recovery at the docking site, as seen in Fig. 1G. The regenerate went on to rapid consolidation within 3 months following placement of the intramedullary nail.

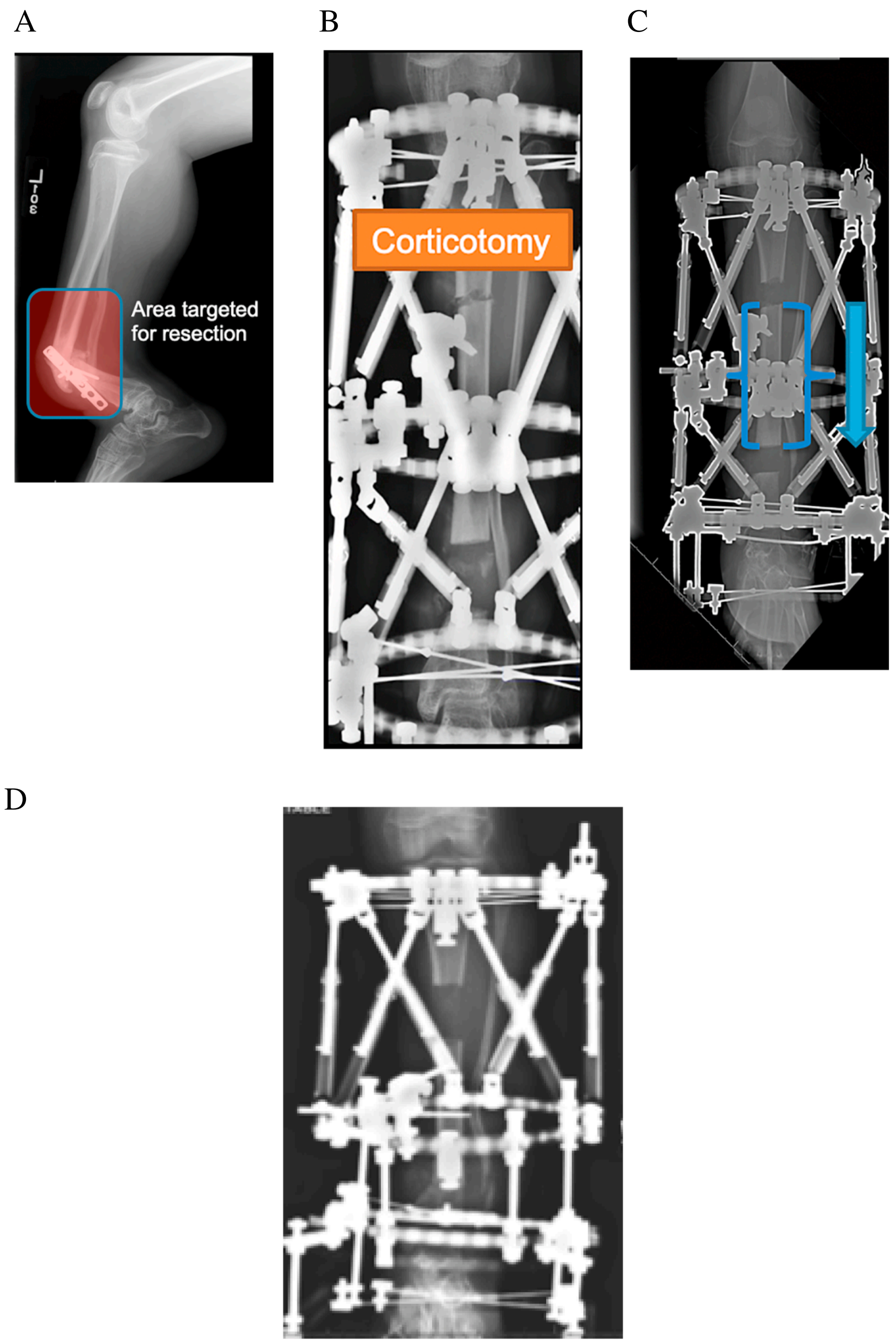


Fig. 4. A: 15-year-old girl with NF-1 and congenital pseudarthrosis of the left tibial diaphysis who underwent a failed ORIF due to complicated hardware failure and nonunion. B: Double-stacked Taylor Spatial Frame for transport and angular correction at two levels. The proximal osteotomy was made at the level of the meta-diaphyseal apex posterior deformity in order to allow for correction of the malangulation. C: Radiograph 3 weeks post-op with the brackets outlining the transport segment and the arrow indicating the direction of the transport. D: Radiograph at 6-week follow-up. E: Radiograph at 16 weeks follow-up. F: Docking site where the nonunion had been present was completely healed. G: Removal of spatial frame and placement of an intramedullar nail. H: Radiograph 6.5 years later showing consolidation and continued remodeling of bone. I: Radiograph 6.5 years later showing consolidation and continued remodeling of bone.

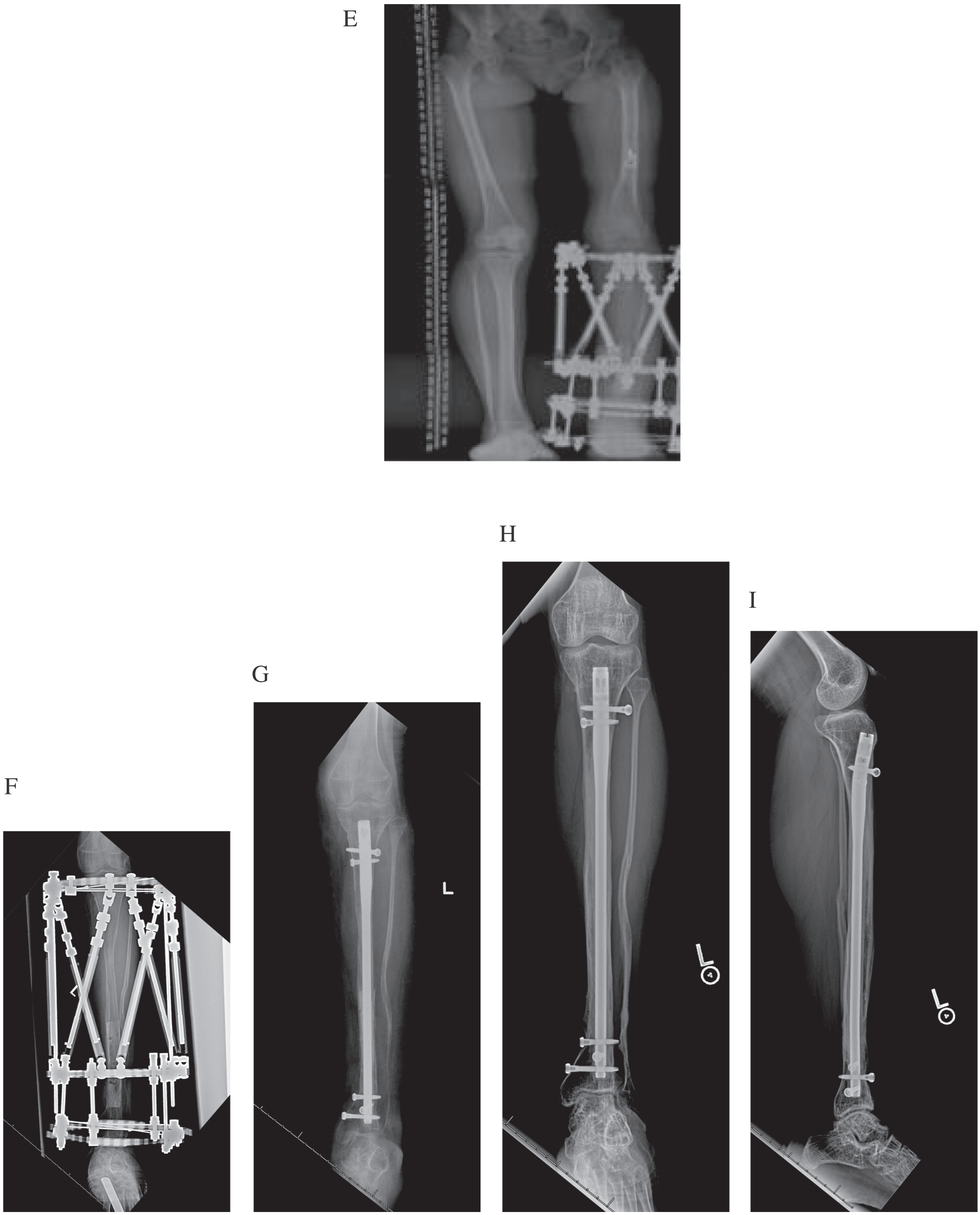


Fig. 4. (*continued*)

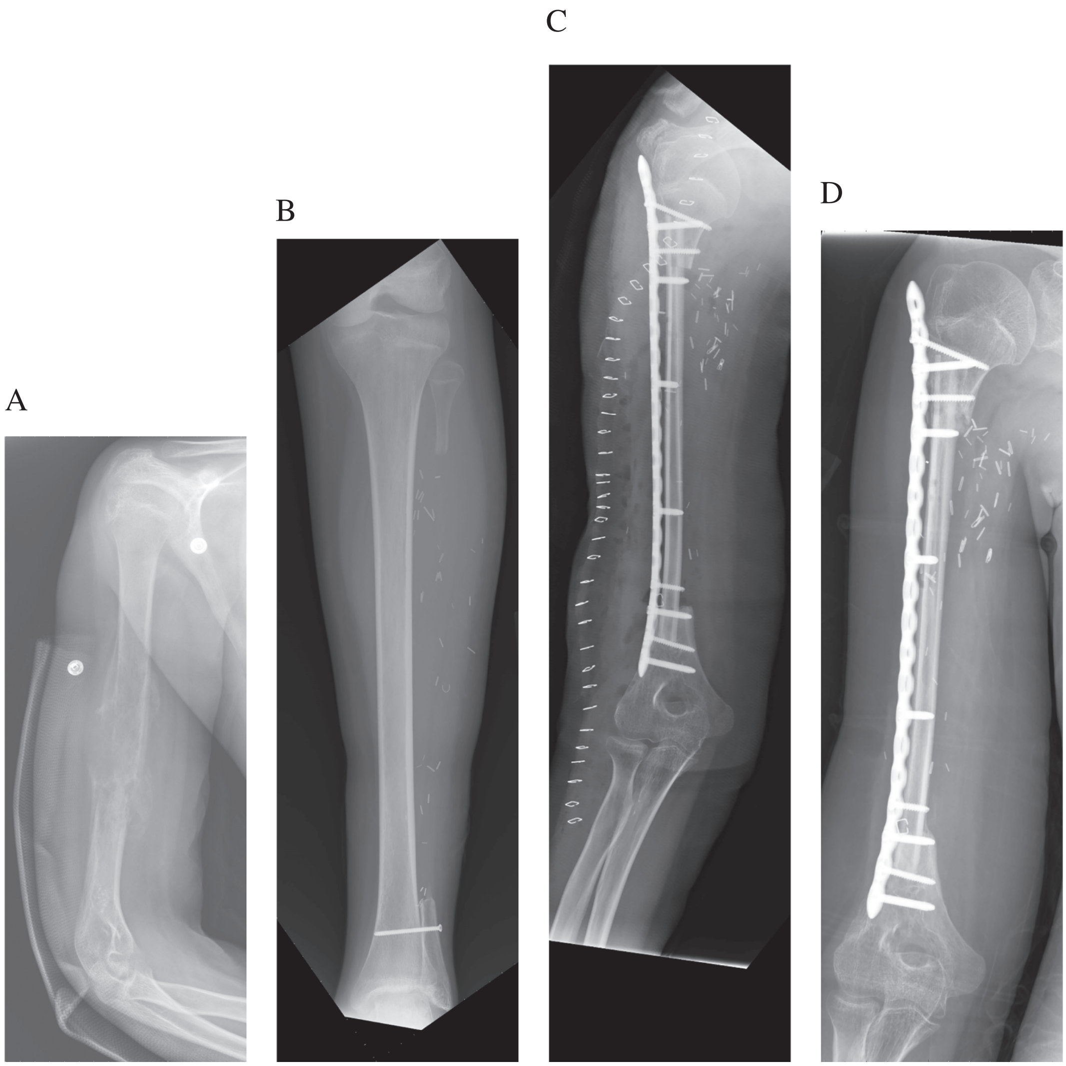


Fig. 5. A: 15-year-old boy with right humeral diaphyseal osteosarcoma requiring resection. B: Fibular graft harvest site. C: Graft was fixed to the proximal and distal humerus using a rigid construct with plates and screws. D: Radiograph 5 months post-op demonstrating adequate osseous integration of the proximal and distal ends of the graft with surrounding callus formation.

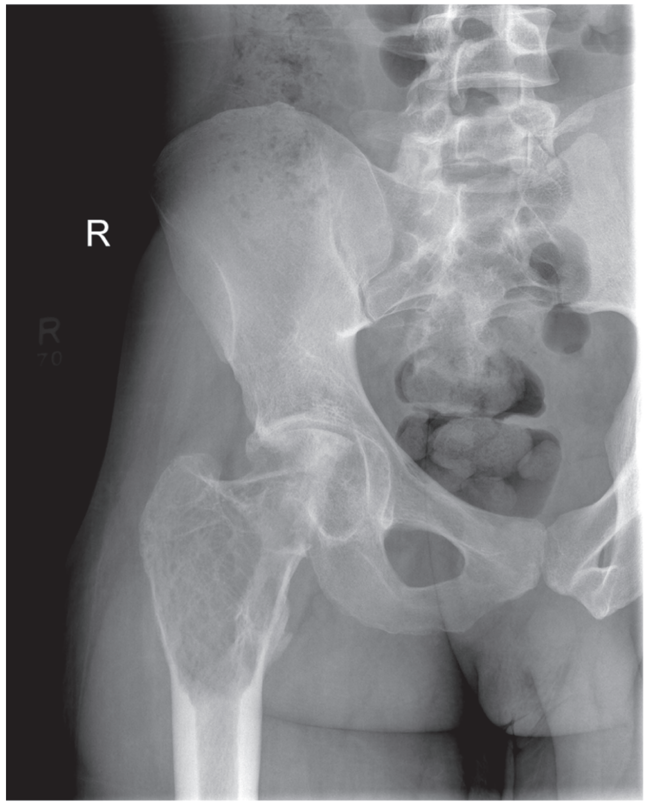
2.2. Case 2

62-year-old man with diabetes mellitus who sustained an open left distal tibia and fibula fractures in a motor vehicle collision. Patient was initially treated outside of the United States using plate and screw fixation.

He presented 7 months post-injury with an 8 cm medial soft tissue defect with exposed bone, exposed hardware, and purulent drainage. His x-ray on presentation is shown in Fig. 2A. Given the nature of the infected wound together with compromised bone and soft tissue it required staged debridement and multi-stage reconstruction. The initial stage consisted of removal of tibial plate and screws, debridement, placement of an external fixation device, joint reduction and limited fixation with pins, and antibiotic beads, shown in Fig. 2B. The second stage consisted of further debridement, removal of the fibular plate and soft tissue closure with intentional shortening and deformity, shown in Fig. 2C [35].

The extent of contaminated bone on presentation and bone loss following multiple debridements made distraction osteogenesis the preferred technique. Two weeks following soft tissue closure there was

A



B

Fig. 6. A: 28-year-old man with proximal femoral fibrosarcoma with intracapsular fracture. B: Extra-capsular type-2 hemipelvectomy and proximal femoral resection followed by vascularized fibular autograft combined with proximal femoral allograft for iliofemoral arthrodesis reconstruction.

Fig. 7. A: 53-year-old man with multiple myeloma with lytic lesions on right humeral head and neck; radiograph after post-radiation therapy. B: Radiograph at post-op after allogeneic bone allograft. C: Radiograph 10 weeks post-op after allogeneic bone allograft. D: Radiograph 7 months post-op after allogeneic bone allograft. E: Radiograph 19 months post-op after allogeneic bone allograft.

sufficient soft tissue healing to begin the bone transport process. Fig. 2D demonstrates corticotomy (osteotomy) site made in proximal healthy bone (blue arrow indicates the direction of the transport and blue brackets indicate the bone transport segment). The external fixation construct is considered a bifocal transport frame with telescopic rods (also known as "clickers") proximally and Taylor Spatial Frame hexapod struts distally. There is also a foot ring attached distally with wire fixation in the foot and no fixation present in the distal articular bone block. Fig. 2E is the radiograph obtained 6 months following the initial osteotomy with docking of the bone transport segment into the distal fracture segment and interval removal of antibiotic beads. Note that the proximal telescopic rods have lengthened, and the struts distally have shortened. The lengthening of the telescopic rods is greater than the shortening of the struts because additional lengthening of the leg was performed using the telescopic rods when the bone transport was complete. Also note that the foot ring has been removed and a combination of tensioned wires and a sagittal plane Schanz pin had been added to the distal articular bone block.

Fig. 2F is a 10-months postop image with interval removal of the distal frame and a healed distal docking site. There is increased mineralization and consolidation at the site of distraction osteogenesis. Fig. 2G was taken 29-months after surgery with notable maturation of bone healing and significant remodeling. Also note the recreation of normal bone anatomy with neocortex and intramedullary canal formation.

2.3. Case 3

30-year-old man who sustained right diaphyseal midshaft femur fracture through a permeative lucent lesion following a fall from standing (Fig. 3A). Differential diagnosis included osteomyelitis, primary bone malignancy, multiple myeloma, and metastatic disease. Subsequent bone scan, Fig. 3B, demonstrated diffusely increased uptake in all phases involving the right mid to distal femur around the pathologic fracture. Further work up with magnetic resonance imaging (MRI), Fig. 3C, demonstrated increased signal intensity within the bone and surrounding soft tissue consistent with osteomyelitis and a large abscess. Subsequent bone biopsy was consistent with osteomyelitis. Initial management was with spanning unilateral external fixation, resection of infected and devascularized cortical bone segments and placement of an antibiotic impregnated polymethylmethacrylate cement spacer to temporarily fill the large defect, sterilize the environment, and create an environment optimally conducive to bone transport (Fig. 3D).

Further debridement of the infected bone was undertaken 2 weeks later utilizing an RIA (reamer, irrigator, aspirator) system in order address satellite lesions of infection within the distal metaphysis. Intraoperative images, Fig. 3E and F, demonstrate the ball-tipped guidewire passing through the intramedullary canal into the femoral condyles (arrow) followed by introduction of the RIA system over the guidewire with subsequent reaming, irrigation and aspiration of bone (bent arrow). A large amount of purulent material was drained, the cement spacer was exchanged, and antibiotic beads were placed in the distal femur (Fig. 3G).

One week later, the antibiotic beads and spacer were removed leaving a 13 cm defect (Fig. 3H). In order to correct the large defect, a distal corticotomy was made and a monolateral rail lengthening system (Modular Rail System) was applied for bone transport (Fig. 3I). Additionally, 40 cc of autograft bone marrow aspirate concentrate was injected into the corticotomy site (arrow demonstrates direction of bone transport).

Fig. 3J was taken 3 months post-op. The distal regenerate formation is very robust. There is also notable heterotopic bone that has formed in the transport gap. This sometimes occurs in the area earlier treated with the antibiotic cement spacer. This is important to note as it can sometimes block progression of the transport. Fig. 3K is taken at 5 months post-op and is now clear that the intervening heterotopic bone will prevent docking of the bone segments without intervention. The distal regenerate is healing well with excellent calcification. Fig. 3 L was taken upon completion of lengthening at 7-months post-op. Fig. 3M, N were taken upon completion of lengthening at 18 and 19 months post-op respectively and demonstrate over time the appearance of a healed docking site and fully consolidated regenerate at the final follow-up while in the fixator and during the first visit after fixator removal.

2.4. Case 4

15-year-old girl with Neurofibromatosis (NF) type 1 and congenital pseudarthrosis of the left tibia diaphysis. She underwent open reduction and internal fixation (ORIF) at age 9 while living outside of the United States. Her course was complicated by hardware failure and nonunion. The radiograph in Fig. 4A reveals that she is essentially at skeletal maturity with at least partial fusion of her physes. The image demonstrates a severely angulated malunion in the distal tibia while in addition there is a compensatory apex posterior deformity in the proximal tibial metadiaphysis and a highly exaggerated anterior distal tibial angle representing a large apex posterior deformity with the CORA (center of rotation and angulation) at the ankle joint. Therefore, the patient has 3 levels of deformity in the tibia that must be addressed in addition to her nonunion fracture and limb length inequality. Treatment began with a resection of the segment of the nonunion. This is necessary because the area of the nonunion represents what is essentially a neurofibromatous tumor within the bone that presents successful healing without refracture. In addition, resection of this segment of bone allowed for crafting of the distal bone segment to have a geometry that will allow for correction of the ankle deformity at the time of docking in additional to optimizing the site of nonunion for healing. A double-stacked Taylor Spatial Frame was applied for transport and angular correction at two levels (Fig. 4B). The proximal osteotomy was made at the level of the metadiaphyseal apex posterior deformity in order to allow for correction of the malangulation.

Fig. 4C shows a 3-week postoperative follow-up radiograph, with the brackets outlining the transport segment and the arrow indicating the direction of the transport. Fig. 4D and E show 6-week and 16-week follow-up, respectively.

At 40 weeks, Fig. 4F, the docking site where the nonunion had been present was completely healed. Progression of healing with increased mineralization at the site of distraction osteogenesis is noted, but the regenerate segment remained weak with a great deal of time left until it would be adequately robust for fixator removal. This fact combined with the ultimate plan to place intramedullary fixation to prevent refracture (which is highly recommended for patients with congenital pseudarthrosis) led us to the decision to proceed with nailing before completion of regenerate consolidation. For this reason, the fixation points within the shaft were removed and debrided and the patient was given a 2-week pin holiday with oral antibiotics before returning to the operating room for removal of the Spatial Frame and placement of an intramedullary nail (Fig. 4G). The patient finished treatment with a healed nonunion site together with full correction of her prior angular deformity and shortening. Fig. 4H, I are radiographs taken 6.5 years post-op reveal further consolidation and continued remodeling of the bone.

2.5. Case 5

15-year-old boy with right humeral diaphyseal osteosarcoma in which wide surgical margins are required at the time of resection (Fig. 5A). A free vascularized fibular flap intercalary autograft was chosen to reconstruct the resultant massive segmental bone defect to provide osteoconductive and osteoinductive properties to enhance the innate healing process. Fig. 5B shows the fibular graft harvest site.

The graft was fixed to the proximal and distal humerus using a rigid construct with plates and screws (Fig. 5C). Fig. 5D shows a 5-month postoperative radiograph demonstrating adequate osseous integration of the proximal and distal ends of the graft with surrounding callus formation.

2.6. Case 6

28-year-old man with proximal femoral fibrosarcoma (Fig. 6A) who suffered of an intracapsular hip fracture. An extra-capsular type-2 hemipelvectomy and proximal femoral resection was performed, followed by vascularized fibular autograft combined with proximal femoral allograft for iliofemoral arthrodesis reconstruction (Fig. 6B).

2.7. Case 7

53-year-old man with multiple myeloma with lytic lesions of his right humeral head and neck post-radiation therapy (Fig. 7A). In this case, a viable allogeneic bone allograft composed of cortical, cancellous, and demineralized cortical bone was chosen due to its osteoinductive and osteoconductive bone scaffold properties as well as its support of osteogenic healing via the introduction of additional bone-derived cells contained within the graft. Initial postoperative radiograph is shown in Fig. 7B, and 10-week, 7-month and 19-month follow-up are shown in Fig. 7C, D and E, respectively.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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