Segmental Bone Loss Reconstruction Using Ring Fixation

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Summary: Ring fixation is a powerful tool in the treatment of bone defects. The ability to create high-quality, biologically normal new bone of even massive proportions using distraction osteogenesis is a major reason for its success. In addition, ring fixation provides the ability to limit the risk of deep infection, improves flexibility in limb length control and alignment, and increases soft tissue coverage options. The drawbacks of ring fixation include long frame times, pin problems, risk of joint contractures, and difficult usage in areas with a large soft tissue envelope such as the thigh. Significant advancements such as hydroxyapatite coated pins, internal cable transport, multifocal transport, and combined techniques with internal fixation have helped increase the effectiveness of ring fixator use by minimizing many of the drawbacks. At present, ring fixation provides the most effective means of treatment for large bone defects in many clinic situations.

Key Words: ring, circular, distraction osteogenesis, distraction histeogenesis, bone defect, transport, open tibia, open fracture

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INTRODUCTION

Segmental bone defects are frequently associated with compromised soft tissue, contamination, and medical comorbidities that make treatment a challenge.[1–3] Paley defined a segmental bone defect as greater than 1 cm, but frequently defects are far more substantial.[4] Circular fixation has been widely and effectively used to treat these difficult problems since Ilizarov introduced his fixator and the concept of distraction osteogenesis (DO).[5,6] Advantages of circular external fixation apart from DO include the ability to gradually correct deformity and control limb length, increase soft tissue coverage options, achieve stable fixation without deep implants in high-risk areas, and perform a truly thorough debridement without concern for increased bone loss.[4,7] In addition, weight bearing is usually permitted throughout treatment.

Unfortunately, the advantages of circular fixation come with significant drawbacks. Circular fixators are uncomfortable and inconvenient for the patient and treatment often require an extended time in the fixator. Cellulitis of fixation pins and wires is common, and preventing joint contractures during treatment requires constant vigilance.[8,9] These issues may not affect final outcome if the patient is compliant and carefully monitored. However, they create a substantial care burden for patient and provider including additional clinic visits, intermittent need for antibiotics, and occasional need for hospital admission or return to the operating room.

Given the high success rates that can be achieved with circular fixation and recognition of the drawbacks of treatment, many efforts have been made to address the associated problems. The development of hydroxyapatite-coated half pins, central bone cable transport, multifocal osteotomies, and combined techniques with internal fixation have proven effective in moderating these concerns. These methods together with new innovations in technique and technology promise to provide progressively more effective methods of bone defects management with ring fixation.

RING FIXATOR CONSTRUCTS

There are many fixator configurations capable of achieving stable fixation and successful DO. Ilizarov discovered DO and pioneered the use of ring fixation to apply this method. He used a frame constructed of threaded rods attached to stainless steel or carbon fiber rings. These rings are fixed to the bone with high-tension wires both proximal and distal to the zone of injury and/or osteotomy site (see **Fig. 1A**, **Supplemental Digital Content 1**, http://links.lww.com/JOT/A146). Transport occurs at an intermediate ring, traditionally stainless steel, that is driven by square nuts. The intermediate ring moves along the threaded rods "rails" and drags the transport segment with it. A column of new regenerate bone forms behind the transport segment and eventually the transport segment crosses the defect to meet the opposite bone end. Half pins can also be used to fix the transport segment to bone and have the advantages of traversing less soft tissue and application with greater crossing angles than wires (see **Fig. 1B**, **Supplemental Digital Content 1**, http://links.lww.com/JOT/A146). However, half pins have larger dimensions and cut a larger path through soft tissue during transport.

Many types of rings are available with variable thicknesses and made of differing materials. These rings can be connected to threaded rods and function the same as an Ilizarov fixator. For this reason, the author refers to a construct of rings connected with threaded rods as an

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Ilizarov-type construct and then names the type of rings, for example, "Ilizarov-type construct with Taylor Spatial Frame rings" (see **Fig. 1C**, **Supplemental Digital Content 1**, http://links.lww.com/JOT/A146). Transport using an Ilizarov-type construct with hexapod rings is straightforward with progression along the threaded rods, but there is a big advantage in that the threaded rod segments crossing the docking site can be changed to struts at the time of docking. The struts then allow for easy adjustment of bone end alignment at the docking site without the need for strut adjustments or changes during transport.

An alterative construct that allows for bone transport and limb lengthening is the bifocal frame. Fundamentally, a bifocal transport frame distracts an osteotomy at 1 location and compresses the gap to bring bone ends together at another site. The lengthening is typically motored by either telescopic rods or square nuts and compression is performed by either square nuts or struts (see **Fig. 1D**, **Supplemental Digital Content 1**, http://links.lww.com/JOT/A146). The bifocal frame with telescopic rods at the distraction site and struts at the docking site is convenient because it allows for biologically friendly distraction with flexibility to adjust docking site alignment without frame modification at the time of docking. This is a powerful construct but requires a many adjustments at 2 levels by the patient and surgeon during the reconstruction.

A special type of bifocal frame is the "double stacked" hexapod (see **Fig. 1E**, **Supplemental Digital Content 1**, http://links.lww.com/JOT/A146). The double-stacked frame is advantageous because there is maximum adjustability of both the regenerate bone segment and the docking site. However, this method of transport requires the greatest number of adjustments by the patient and strut changes by the surgeon, is by far the most expensive, has the most hardware obscuring radiographic evaluation, and is mechanically less rigid. For these reasons, the author generally reserves this construct for special situations that require additional flexibility in alignment such as soft tissue coverage, deformity correction with multiple CORAs (centers of rotation and angulation), or malalignment between the segments across regenerate column at the end of transport.

An alternate construct is the cable transport frame. **Supplemental Digital Content 1** (see **Fig. 1F**, http://links.lww.com/JOT/A146) shows an example of a balanced cable transport frame with internal cables pulling the transport segment. Note the absence of pins and wires in the transport segment and the attachment to a strut proximally used to motor the transport.

DISTRACTION HISTEOGENESIS

Distraction histeogenesis is a biologically friendly process that allows for generation of high-quality biological tissue, including bone, that recapitulates the qualities of the native tissue. The term distraction histeogenesis is used specifically to note that all tissues in the extremity, including nerves, blood vessels, and other soft tissue, participate in the regenerative process under varying circumstances. When applied specifically to bone, the term DO is used. Bone formed through DO is normal in appearance and biological behavior, which is distinct from the sclerotic bar bone most often achieved with bone grafting techniques. **Supplemental Digital Content 2** (see **Fig. 2**, http://links.lww.com/JOT/A147) illustrates the difference in appearance of bone reconstructed with induced membrane bone grafting[10] contrasted with DO. Systematic literature review has shown that worldwide success rates for addressing bone defects and achieving bony healing with DO are very high (80%–99%).[3]

MODERATING DEEP INFECTION RISK

The risk of deep infection in the treatment of bone defects is relatively low with ring fixation compared with other methods. Several factors likely contribute to this difference. One factor is the ability to avoid placing deep implants across the bone defect where compromised soft tissue and wound contamination are common. This is inherently helpful because there is no deep implant present around which bacteria can colonize and create a protective biofilm.

Not placing deep implants also prevents compromise of local blood supply in the zone of injury. It is protected because there is no loss of the intramedullary supply from an intramedullary nail (IMN) and no stripping and/or periosteal blood supply loss from an overlying plate. It is worth noting that, although studies have demonstrated an augmentation of blood supply 2–3 weeks after intramedullary nailing of closed tibia fractures,[11] in a contaminated area, even a temporary loss of blood supply may allow bacteria to overwhelm local host defenses and establish infection.

Another factor is that the surgeon may perform a more aggressive bone debridement knowing that DO can effectively address the additional bone loss. In addition, the ability to treat defects without bone graft avoids the potential risk of placing devascularized bone in the zone of injury. It is currently unclear how much each of these factors contributes to modification of infection risk, but it is likely they are all relevant.

HYDROXYAPATITE-COATED HALF PINS

Hydroxyapatite (HA)-coated half pins are a major advancement in decreasing the risk of pin site complications. Uncoated half pins tend to loosen rapidly and develop infection and unlike wires they are impossible to re-tension for stability. Animal studies demonstrate decreased infection rates and increased pin extraction torque over time with HA pins as opposed to the gradual loss of fixation seen with uncoated pins.[12–14] Clinical data confirming greatly decreased loosening and infection rates with HA pins were first published in 1998[15] and have subsequently been confirmed by many others.[16,17] The improved fixation and longevity of HA-coated half pins is especially important for definitive fracture management for which their use is now considered standard by many surgeons.

CABLE TRANSPORT

Central cable bone transport has proven effective at decreasing soft tissue complication. Cable transport methods use a long braided cable linked to the transport segment internally to pull the transport during DO. These methods avoid having pins and wires drag through the skin during bone distraction and thereby substantially decrease pain, decrease pin cellulitis from local soft tissue necrosis at the leading edge of advancing pins, and eliminate the linear scarring associated with a traditional transport frame. In addition, cable transport eliminates the risk of damage to soft tissue flaps and compromised skin during the transport process. Reported results from cable transport have been very encouraging with a 100% union rate and very low rate of infection.[18–20]

MULTIFOCAL TRANSPORT

DO performed simultaneously at multiple osteotomy sites has been proposed to decrease healing time for massive bone defects.[21,22] Most commonly a trifocal transport is performed in which there are 2 osteotomy sites that are distracted and a bone defect zone that is gradually compressed (see **Figs. 3A–F**, **Supplemental Digital Content 3**, http://links.lww.com/JOT/A148). The benefit of this technique is that transport and consolidation can be more rapid because they are happening at more than 1 site simultaneously. Distraction times for multifocal transports have been reported to decrease by as much as 2.5× (from 26 to 10 d/cm).[23] There is also a significant effect on bone healing index (BHI) with a decrease from 1.5 to 1.0 mo/cm in 1 series and to 1.2 mo/cm in another.[23,24]

It is interesting to note that the decrease in healing time is less than that which would be expected if the BHI were to be divided by the number of osteotomy sites. For instance, a traditional Ilizarov transport would be expected to have a BHI of 1.5–1.8 mo/cm. If BHI were equally divided by the number of osteotomy sites, then 2 osteotomies would heal in 0.75–0.9 mo/cm and 3 in 0.5–0.6. However, this is not observed clinically.

There are 2 main reasons for this disparity. The most problematic of these is that pins and wires drag through the skin during transport, causing a leading zone of pressure necrosis that causes pin irritation. The skin can generally compensate and fill in from behind when the pins travel at 1 mm/d. However, distraction at multiple sites can cause the skin to experience much greater stress and the body can no longer compensate, leading to progressively more severe teardrop-shaped ulcerations trailing the pins (see **Figs. 3G–L**, **Supplemental Digital Content 3**, http://links.lww.com/JOT/A148). This is especially true for tandem transports in which both bone segments are moving in the same direction. As a result, it is necessary to decrease the transport rate to less than 1 mm/d at each osteotomy site.

The other consideration is that at least 1 osteotomy must be made at a disadvantageous location. Shaft and distal osteotomies are well known to heal more slowly than proximal metadiaphyseal osteotomies. Therefore, forming 2 regenerate columns each with half of the length will allow more rapid healing of the proximal metadiaphysis but leaves a shaft regenerate with a potentially very extended healing time (see **Figs. 3B, D, F**, **Supplemental Digital Content 3**, http://links.lww.com/JOT/A148). These facts are key in guiding decisions that optimize healing and decrease complications during multifocal transport.

COMBINED METHODS WITH INTERNAL FIXATION

Lengthening Over a Nail

The modern concept of lengthening over a nail (LON) was introduced with the intent of achieving shorter external fixation indices (EFIs), decreased refracture rate, and improved alignment.[25] Many authors have reported on LON techniques and almost universally confirm decreased EFIs ranging from 14.1 to 33 d/cm.[26–35] Refracture rates are improved and rates of bony union at the conclusion of treatment are high. Overall alignment is somewhat improved, but there is a proven tendency toward valgus malalignment of the proximal tibia.[36] Despite these successes, the biggest concern with LON is an increased risk of deep infection. This risk has been moderate in some reports of limb lengthening[29,33] but is more pronounced with long lengthenings or with transport for bone defects.[30,32,34] Difficulty in keeping pins and wires remote from the nail in these cases is most often cited as the reason for increased infection risk, but poorer soft tissue envelope and a greater potential for contamination of the defect site are also possible causes.

Despite the risk of infection, LON techniques have achieved equivalent or improved functional results and rates of bony union over traditional transport.[3] However, it is notable that BHI have been variable with authors reporting results both better and worse than traditional transport. A systematic review of LON in 2012 confirmed that EFI is substantially decreased but concluded that there is no reliable evidence that consolidation time or complication rates differ from traditional transport.[37] Review of these studies and subsequent reports reveals a BHI of 1.83 (0.87–4.4) mo/cm with all reports included and 1.60 (1.36–2.07) mo/cm when the best and worst report were eliminated.[26–35,38,39] These results are consistent with expectations from a traditional Ilizarov transport.

There are theoretical reasons why LON could have faster or slower BHI than traditional transport. Faster healing is favored by the greater stability conferred by the IMN. Slower healing may occur because of effects on regenerate blood supply and regenerate volume. Blood supply is decreased because of damage to the medullary supply during reaming and placement of the IMN. Although blood flow rebounds after 2–3 weeks, the decreased flow is present during the critical time of latency and early distraction when the initial callus and regenerate column form. Ryu studied the quality of regenerate using pixel value ratios at intervals during transport and the shape of callus at the end of distraction.[40] He found strong evidence that regenerate formed was better when transport was performed without the presence of an IMN. They attribute this difference to effects on regenerate blood supply. In addition, regenerate volume is also decreased with LON because the amount of regenerate is decreased in total volume by the space occupied by the nail. Despite the concerns, the lack of difference in BHI between reports of LON and traditional transport make it likely that the competing factors balance to eliminate a notable difference.

Transport With a Locking Plate

Transport with a locking plate (TLP) is an alterative to LON for shortening EFI. Oh reported 10 patients with moderate-sized defects of 5.9 cm treated with TLP. EFI was 13.4 d/cm, which is similar to LON. Weight bearing was protected longer than with other methods including a patellar tendon weight-bearing brace for 10–12 weeks after frame removal. BHI was slower than other methods at 64.5 d/cm. However, there was a 100% union rate and excellent alignment with only minor complications.

Many authors have reported DO followed by locked plating.[41–44] These reports show success in decreasing EFI to between 14 and 19 d/cm. Some of these report a substantial risk of plate breakage and varus malalignment, which explains why an extended period of protected weight bearing may be necessary.[43] Despite this, these methods have high union rates and BHIs are commonly 1.5–1.6 mo/cm commensurate with LON and traditional bone transport.

Transport and Then Nailing

Reports of DO with planned conversion to intramedullary nailing are more limited. Limb lengthening and then nailing (LATN) was first published in 2008.[45] The EFI of 0.5 mo/cm was 3.8× faster than the classic comparison group, and the BHI of 0.8 mo/cm was 2.4× faster. The EFI is similar to successful LON or TLP, but the BHI is much faster. They had a low infection rate of 2.5% because of a single case that was successfully cured of infection after bone healing.

Despite the success of LATN for limb lengthening, there are only 3 reports of bone transport with planned IMN conversion. This is likely because, as opposed to limb lengthening, there is a transport segment with contaminated fixation pins and wires in the intended IMN path. Two reports used a period of frame removal, "pin holiday," with intravenous antibiotics before IMN to mitigate the risk of infection, despite the inherent risk of limb shortening and regenerate rebound during the pin holiday.[46,47] Infection rates were 0/10 (0%) and 1/17 (6%); EFIs 10.2* and 16.5 d/cm; and consolidation indices 16.7* and 36 d/cm (*Selim reported EFI and consolidation index based on initial defect and not on lengthing achieved. The numbers listed correct for this error.). EFI was the same as with LON in one report and faster in the other where a trifocal transport was used. BHI was not provided by either author.

An alternative method uses balanced cable bone transport with immediate planned conversion to IMN (TATN) with no pin holiday.[20] This allows maintenance of anatomic alignment and length in the ring fixator during nailing. EFI of 13.2 d/cm is similar to LON, but BHI of 0.81 mo/cm is much faster. The trifocal transport subgroup was even more rapid with EFI of 10.0 d/cm and BHI of 18.2 days (0.55 months)/cm. The BHI between LATN and TATN methods are virtually identical at 0.81 and 0.80 mo/cm, respectively, confirming the beneficial effect of this strategy on regenerate consolidation.

CONCLUSIONS

Ring fixation has a long record of proven success in managing bone defects and is the treatment of choice in many circumstances. Many efforts have been made to address the drawbacks of ring fixation. Hydroxyapatite-coated pins have greatly decreased half pin complications and increased fixator stability through the course of treatment. Cable transport methods have decreased scarring and pain during bone transport. Multifocal transport, although technically more challenging and prone to complication, is capable of decreasing EFI and BHI.

Combined methods of LON and TLP are effective at decreasing EFI and have high union rates, but no effect on BHI or complication rates. Bone transport with planned IMN conversion decreases EFI as much or more than LON and TLP methods. Cable transport TATN reduces BHI substantially more than other methods. Despite concerns over infection, combined methods with internal fixation have shown potential in realizing the benefits of ring fixation while minimizing the drawbacks.

The holy grail of bone defect management is a fully synthetic graft that rapidly incorporates to become biologically normal bone, such as the bone formed with transport, which can be combined with internal fixation with no associated risk of infection. Unfortunately, current options fall far short of this idealized goal. Until such options are available, ring fixation provides the most powerful tool in bone defect management in many scenarios and also provides options for soft tissue management, limb length adjustment, alignment control, and stable fixation throughout healing.

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