14 Bone Defects

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INTRODUCTION

The treatment of bone loss, occurring as the result of acute trauma or segmental resection for reconstructive procedures in the skeleton, has traditionally been a complex surgical problem. Numerous procedures have been devised to reconstitute bone stock, obtain fracture union, and provide a stable functional limb.

In an attempt to avoid the problems associated with deficient graft materials and free tissue transfers, internal bone transport is a technique that has been a successful methodology for bony reconstruction for both acute and reconstructive bone loss (1).

CLINICAL EVALUATION

Most published reports utilizing bone transport have dealt primarily with nonunions or infected nonunions for which transport techniques are undertaken as a planned elective procedure. The situation is more complex when the surgeon has to deal with segmental defects following an acute traumatic situation. Fractures often will have extensive soft-tissue loss in concert with large skeletal defects. For these types of injuries, the principles of open fracture management must be adhered to prior to the institution of bone transport techniques.

When considering bone transport in an acute or chronic situation, it is paramount to determine if a biologically sound healing environment is present or can be achieved at both the site of the proposed corticotomy and/or the docking sites. The success of both corticotomy and solid docking involves well-vascularized segments of bone and soft tissue (2). If soft-tissue incompetence (dysvascularity) is present at the proposed corticotomy site, the production of healthy regenerate may be compromised (3–5). Severe open fractures with a wide zone of injury are often associated with very poor soft-tissue coverage at the site of injury (6). Associated soft-tissue compromise may be coexistent elsewhere in the limb, which may involve the site of the proposed corticotomy.

The periosteal blood supply is derived primarily from the surrounding soft-tissue envelope. If this is inadequate and unable to provide a vascularized, viable periosteal sleeve, the prospects for the development of an inadequate regenerate is very real. In these situations, an alternative corticotomy site, performed through healthy tissues, should be selected.

Solid healing of the docking site requires all the biologic components necessary to heal what is equivalent to an acute fracture. The ability to revascularize the ends of the docking segments and facilitate the migration of pluripotential cells is dependent on the revascularization process. If the docking fragments are excessively mobile, the moving bone ends will traumatize the local blood supply. Thus, the influence of a stable mechanical environment facilitates docking site union. The hallmark of these events is the inflammatory phase of fracture healing that promotes the revascularization process. This area must be manipulated to provide the appropriate vascular response either through aggressive debridement or through soft-tissue coverage techniques.

In cases of infected nonunions, draining sinuses with atrophic and scarred soft tissues are often present at the nonunion/proposed docking site. Consideration of these issues helps to determine the extent of nonviable tissue debridement necessary to obtain healthy vascular tissue. Magnetic resonance imaging can be helpful to determine the extent of marrow dysvascularity found in a proposed transport segment or proposed docking site (4,7–10). Additionally, arteriography may also be useful to determine distal vascularity (blush) with regard to docking segment viability as well as soft-tissue viability (Fig. 1).

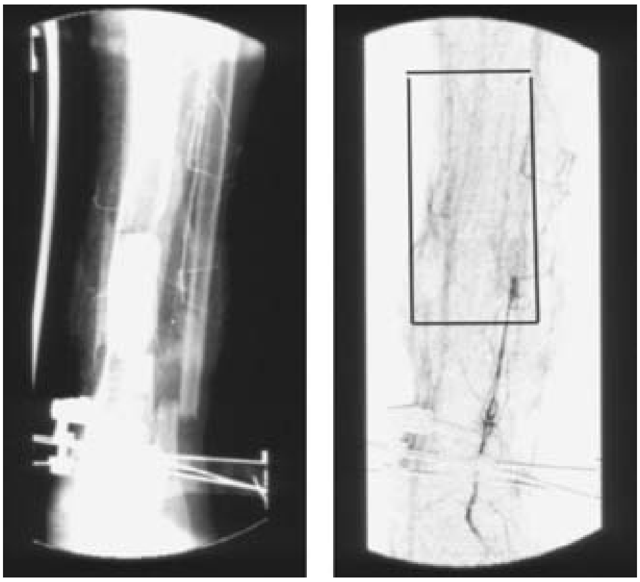

Figure 1 Angiogram of tibial defect prior to corticotomy and transport. Note well-vascularized transport tract and docking site blush (*black outline*).

If the soft-tissue defect is similar in size to the bone defect, then soft-tissue transport in conjunction with the bone transport is possible (11,12). Tissue loss that exposes bone is not amenable to combined soft-tissue/bone transport without first addressing the exposed bone. This is accomplished through rotational or free tissue transfer to cover the bone. Alternatively, the bone should be resected back until healthy soft tissue covers the bony segment (6,12,13).

TREATMENT OPTIONS

During the initial presentation of an acute traumatic defect, a simple monolateral, four-pin external fixator is applied to the limb (Fig. 2). Every effort should be made to remove any

Figure 2 (**A**) Severe open tibia stabilized with a simple four-pin external fixator. (**B**) Antibiotic block placed beneath free flap coverage to maintain prospective transport pathway prior to frame application. In this case, the flap was placed prior to transport frame placement. The usual circumstance is to place frame before free flap application.

Table 1 Clinical Management

	Degree of Bone Loss	Soft-Tissue Integrity	Vascularity Vasculature/Small Vessel Disease	Pearls of Management	Potential Complications
Bone transport	> 3–4 cm	Competent at corticotomy, transport and docking sites	Vasculature intact no small disease (good)	Antibiotic beads in transport tract	Modulate distraction rate site to avoid deficient regenerate; Graft docking site
Bone transport with open wound	> 3–4 cm	Incompetent at nonunion or fracture site	Good	Flap coverage over transport/docking site	Transport tract cutting through flap pedicle
Bone and soft-tissue transport	No minimum defect size	Incompetent	Dysvascular limb; small vessel disease	Resect bone back to healthy bone until covered by granulation soft tissue	Poor regenerate. Invagination of soft tissue into transport tract
Acute shortening	<4 cm	Incompetent	Dysvascular limb; small vessel disease	May bridge larger defects with gradual shortening 0.5 cm per day	Kinking of vasculature; bunching necrosis of soft tissues
Combination transports	Massive >10–12 cm	Competent	Good	Bifocal, trifocal treatment; fibular transport	Number of potential complications rises exponentially with complexity of transport

devitalized bone and necrotic soft tissue. The patient is returned to surgery every 48 hours for additional irrigation and debridement procedures until the zone of injury has declared itself, and the wound has become culture negative. At this point, the decision to proceed with transport is made (6,13–15). This strategy should also be employed when initiating a staged reconstruction for an infected focus. Alternatively, acute or gradual shortening offers advantages over transport in the patient who presents with vascular insufficiency, i.e., a one vessel leg where free vascularized tissue transfer is contraindicated. Cases in which the patient has a systemic small vessel disease process, i.e., diabetes, severe peripheral vascular disease, connective tissue disorder, etc., are also candidates for shortening strategies (6,9,16–19) (Table 1).

Shortening acutely can be accomplished safely for defects up to 3 to 4 cm in the tibia. More shortening can be tolerated acutely in a femoral defect up to 5 to 7 cm. In some situations, it is advantageous to decrease the transport distance and thus time in the frame. Shortening aids in soft-tissue coverage by decreasing tension and gaps in the open wound; this approach may allow wounds to be closed by delayed primary closure, or healed by secondary intention or simple skin grafting. With this technique, one may avoid extensive free flap coverage (Table 1) (6,10–12,17).

Acute shortening of more than 4 cm can cause the development of tortuous vasculature and actually produce a low flow state with detrimental consequences. Open soft-tissue wounds when acutely compressed can become notably bunched and dysvascular, with the development of significant edema and the possibility of additional tissue necrosis and infection (11,12,14,16). More than 4 cm may be safely accomplished in the femur; however, similar problems with wound edema and bunching may occur (1,20,21).

If the defect is larger than can safely be closed acutely, a gradual shortening can accomplish the same goals. Shortening at the rate of 0.5 cm per day in divided doses will rapidly oppose the skeletal defect as well as avoid the detrimental soft-tissue consequences and vascular element kinking of acute defect compression (6).

Massive defects, greater than 8 to 10 cm, are candidates for combined treatment options. The success of massive transport is directly proportional to the number of complications associated with these rigorous reconstructions (4,8–10,14,15,17,20–23). It is recommended that combination methodologies be initiated with great caution, in cases where all transport parameters are optimized, i.e., intact vascularity, small vessel disease, intact soft-tissue sleeve, etc. (1,8,16). Acutely shortening the defect can reduce the transport time required to achieve docking. Once docking is accomplished, straightforward lengthening can then be carried out. The ability to stop the lengthening process is available for patients who may experience "frame fatigue" during a prolonged bone transport. It is much easier to stop a lengthening procedure and allow the lengthened regenerate to consolidate with the only morbidity being a short functional limb. Alternatively, once a stable limb has been achieved, delayed lengthening can be accomplished by alternative measures such as lengthening over an intramedullary (IM) nail or achieving resolution using an internal lengthening nail. Alternatively, it is very difficult to salvage a limb if transport is stopped during mid-distraction prior to docking.

Bifocal and trifocal strategies can be employed such as double-level transport in combination with acute shortening (4,8,9,16,17,22). Free vascularized fibula, combined with acute shortening and bone transport, has also been reported as a methodology to reduce the substantial frame time required for massive bone defect reconstruction (1,13). Transport over nails has also been employed for larger defects in both tibial and femoral deficiencies (1,21,24). Lastly, transverse ipsilateral fibular transport has been reported for reconstruction of massive tibial defects.

For acute bone loss, it is advantageous to avoid local rotational flaps because the rotated muscle is often involved in the acute zone of injury, and thus performing a rotational myoplasty may further damage a compromised muscle. Ultimately, the additional vascularity supplied by this compromised muscle may be of minimal value. The use of free tissue transfer helps to provide a well-vascularized tissue bed through which bone transport, docking, and eventual healing of the docking site can occur.

Once a healthy wound is achieved, a specific bone transport frame is then applied. It is much easier to perform a radical debridement in the presence of a simple external fixator, rather than through and around a complex bone transport device. Although access is more difficult for the plastic surgeon, it is preferable to have the transport frame in place prior to the placement of the free flap. In this way, the vascularized pedicle can be planned and located away from any transport wires or pins that may eventually impinge upon the flap anastomosis.

SURGICAL TECHNIQUE

The majority of bone transport is performed for tibial defects. A basic tibial transport frame consists of a multiple ring construct. Depending on the size of the limb in question, anywhere from three to five rings may be used. For a proximal or midshaft defect, a single proximal ring will be attached, parallel to the knee joint, at the level of the fibular head. For more distal tibial defects, two proximal rings can be utilized (Fig. 3).

For distal one-third tibial bone loss, the distal fixation segment is not large enough to accommodate two rings, and therefore only one distal ring is used. A single, intermediate transport ring is utilized. The proximal and distal ring blocks are attached to each other by four long-threaded rods. Location of the rods on the rings can be varied to allow for large open corridors, to facilitate plastic surgeon's placement of free flaps with the frame in place. The transport ring is placed midway on the four long-threaded connecting rods. Initially, this ring is left to "float" up and down on the four connecting rods. Frames should be preassembled to facilitate mounting in surgery (Fig. 4).

Precise placement of the frame is crucial to ensure that the proposed docking side is aligned with sufficient cortical contact for union to occur (Fig. 5). The preassembled frame is placed on the limb, and a transverse 1.8 mm wire is inserted as a proximal reference wire. This wire is placed parallel to the knee joint at the level of the fibular head, attached and tensioned to the proximal ring.

A transverse olive wire or perpendicular schantz pin is next placed into the proximal ring fixation block. Once the overall alignment of the frame is confirmed, the wire is tensioned, or the half-pin is connected to the ring, locking the proximal limb segment in place and preventing the frame from shifting during subsequent distal fixation. If shortening has occurred or the limb is acutely shortened intentionally, a proximal fibular capture wire or half-pin construct should be utilized to avoid dislocation of the proximal tibia–fibula joint when limb lengthening occurs (Fig. 6).

The distal ring fixation proceeds with the insertion of a smooth 1.8-mm reference wire at the level of the distal ring, parallel to the ankle joint line. The wire should be placed just anterior to the fibular shaft in the lateral view. The single smooth wire in the distal segment will be used to ensure appropriate alignment of the docking site in both the coronal and

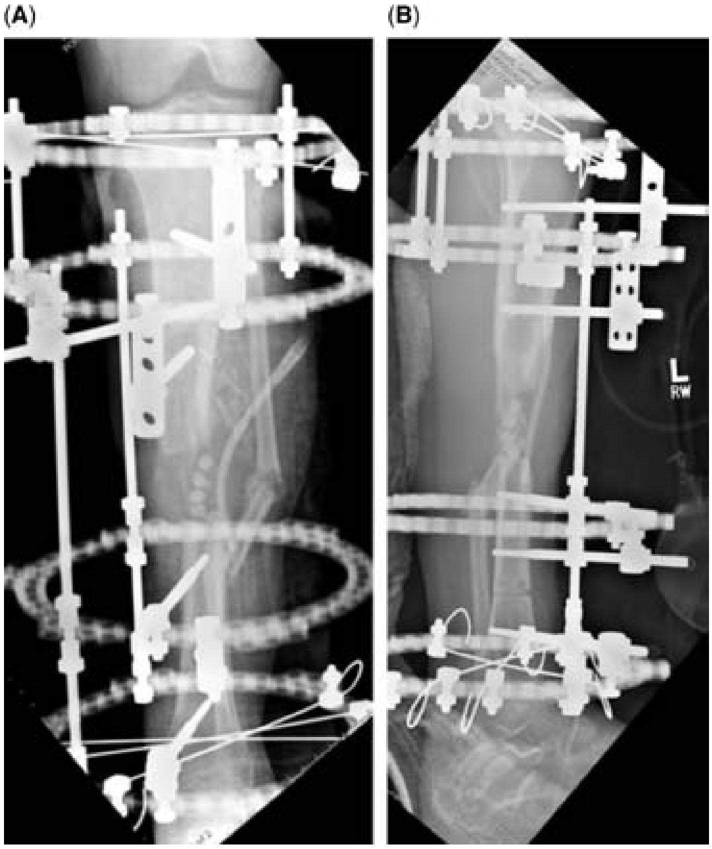

Figure 3 (**A**) and (**B**) Four-ring frame application following removal of antibiotic spacer. A distal corticotomy was selected. The limb was acutely shortened decreasing total transport time. A short chain of antibiotic beads is placed into transport tract.

the sagittal planes. Prior to attaching the solitary distal wire, the anteroposterior displacement of the proposed docking site is corrected. The image intensifier is utilized in the lateral position to view the segmental defect region. The distal fragment can be raised or lowered appropriately to align the posterior cortices across the defect. When the correct anteroposterior alignment is achieved, the smooth wire location is noted on the ring and the wire fixation bolts are attached to the ring at this location.

The image intensifier is now positioned to obtain an AP view of the segmental defect proposed docking site. Because only one smooth transverse wire is present distally, the entire distal fragment including the fibula can be translated on the smooth wire in order to correct any translational offset.

The distal segment is thus moved on the smooth wire in a medial or lateral direction until the lateral cortices above and below the defect are aligned. It may be helpful to position a threaded rod along the lateral cortex to gauge the adequacy of alignment in both the AP and the lateral views. After correct alignment is achieved, a second smooth wire is placed as a distal fibular capture wire. This wire locks in the position of the distal fragment and the proposed alignment of the docking site. This is followed by application of the remainder of distal fixation, using tensioned wires or half-pins as per surgeon's preference.

The intermediate transport ring is left unattached to the bone, especially if further plastic surgery is contemplated. The ring is "floated" in a proximal or distal location, out of the region of the open wound and proposed plastic surgery procedures. A reciprocating saw can be used to achieve congruent surfaces on the ends of the proposed transport and docking segment. An antibiotic cement spacer can also be placed across the defect. The block should be oversized to achieve a wedging effect into the defect, which confers additional frame stability by achieving temporary cortical contact (Fig. 3).

At the time of free flap or primary closure, the antibiotic spacer is removed, and a solitary chain of antibiotic cement beads is placed into the defect (Fig. 4). The beads provide and maintain a "potential space" or fibrous tunnel through which the transport segment will

Figure 4 (**A**) Autodistractors used as transport "motors" sliding segment proximally onfour long-threaded rods (guide tracks) The transport ring attached to bone using 90° divergent 6 mm HA pins. Note the pins are attached proximally in the transport segment to "pull" the bone. The antibiotic beads have been exchanged for bone graft at the docking site. (**B**) Distractors removed and docking site compressed until healed and regenerate has consolidated. (**C** and **D**) Frame removal following healing of docking site and maturation of the regenerate with slight translation of docking site. Lateral view shows anatomic alignment with solid union at docking site.

travel. If the wound is closed primarily, antibiotic beads are still used to prevent invagination of the intact soft-tissue envelop into the transport pathway.

If combined soft tissue and bone transport is considered, then the bone must be resected back until covered by healthy remaining tissue (Fig. 7). The region of the proposed transport tract may be completely devoid of covering tissue, and this area is allowed to granulate. Once healthy tissue is achieved in this location, it can be covered with a split thickness skin graft

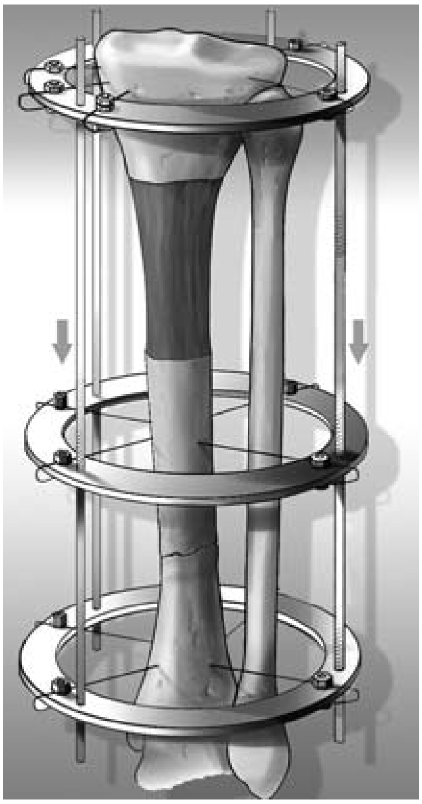

Figure 5 Three-ring transport frame with proximal and distal reference wires.

and transport of the segment undertaken. Other times, the bone and soft-tissue defect close simultaneously, with transport obviating the need for any plastic surgery coverage.

Transport should be delayed for at least three weeks following free flap coverage. The delay allows the free flap anastomotic site to become fully epithelialized and healed and is then able to withstand the inevitable tension forces that will be subjected to it during transport. If the wound is closed primarily or bone resected back to healthy tissue, corticotomy and transport can be undertaken immediately.

Two methods are commonly used to transport the bone segment. Traditional fixation of the transport segment is accomplished using obliquely placed olive wires across the transport segment. The resultant pull vector of these wires should be parallel to the bone axis. These wires exit inferiorly through the soft tissues. These free wires are attached to the distal ring using a slotted rod on a hinged assembly. The angle of these wires changes as the transport progresses, and this is accommodated by a hinge on the pulling mechanism (Fig. 8).

Once the transport segment approaches the distal docking site, the longitudinal wires are exchanged for transverse wires and attached to the intermediate transport ring. This is done to maintain constant compression at the docking site.

The second method of transport utilizes a transport ring throughout the entire treatment. The ring is positioned at the mid to distal third of the proposed transport segment. The eccentric location of the transport ring is chosen because the ring will "pull the bone" into docking position rather than "push the transport segment." A "pushing" construct occurs if the ring and bone attachment is located closer to the corticotomy, rather than the docking end of the transport segment. This "pushing" construct results in an unstable transport segment that will have a tendency to deviate during transport (Fig. 4). A useful analogy is that it is easier to pull a string of spaghetti (transport segment) into a straight line, rather than trying to push it into a straight line.

The transport ring is rigidly fixed to the bone by utilizing transverse tensioned wires or half-pins placed on either side of the transport ring. It is recommended that two 6-mm half-pins be utilized for segmental transport, and that the half-pins be placed at 90-degree angles to each other (Fig. 4). This pin orientation avoids excessive cutting through the

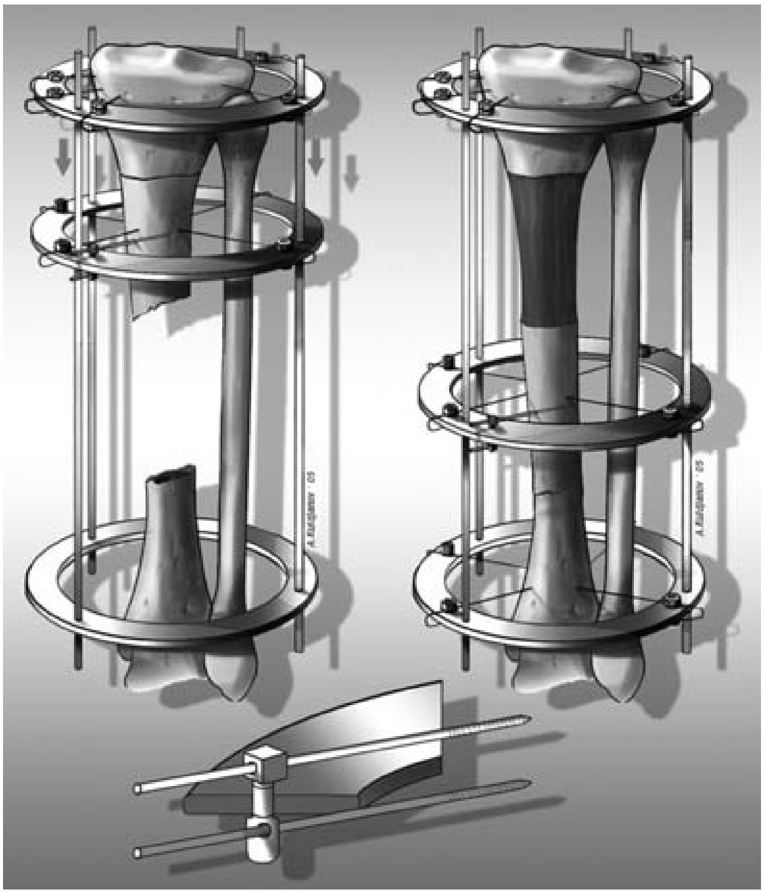

Figure 6 Ring transport using either transverse wires or two Schantz pins mounted above and below the transport ring.

transport tract. Parallel orientation of transport half-pins has been reported to cause a ''double-hit'' wound dehiscence. The first transport pin cuts through the soft tissues, and just as the transport tract begins to heal, the second pin reopens the same tract with subsequent wound breakdown (13).

Another way to assemble the transport frame is for simultaneous but independently controlled shortening and lengthening. This can be connected with rods or Taylor spatial frame struts. In this manner, the defect shortening can be performed faster than the regenerate lengthening, leading to earlier docking at the nonunion site. The fibula cannot be intact if differential shortening and lengthening is to occur.

Half-pins and transport wires will easily cut through a free flap; however, one must note the location of the flap anastomosis to ensure that transverse transport wires or half-pins will not impinge on this area.

Following fixation of the transport segment, a proximal or distal corticotomy is performed. In cases of acute bone transport following high-energy fractures, a wide zone of injury is often present. It is better to perform the corticotomy away from any region of previous soft-tissue compromise or zone of injury and, as such, double-level transport with two corticotomies is not easily achieved (Fig. 4).

Double-level transports have been performed in cases of large bone defects. These complicated reconstructions have been associated with a high rate of complications as well as nonunion of the corticotomy site. However, if double-level transport is to be carried out, additional proximal or distal transport rings will be required as described above (4,8,13,22,23).

Bifocal Approach

This is called bifocal because there are two segments with activity. One segment (the defect) is undergoing compression/shortening, and one segment (the bony regenerate) is undergoing

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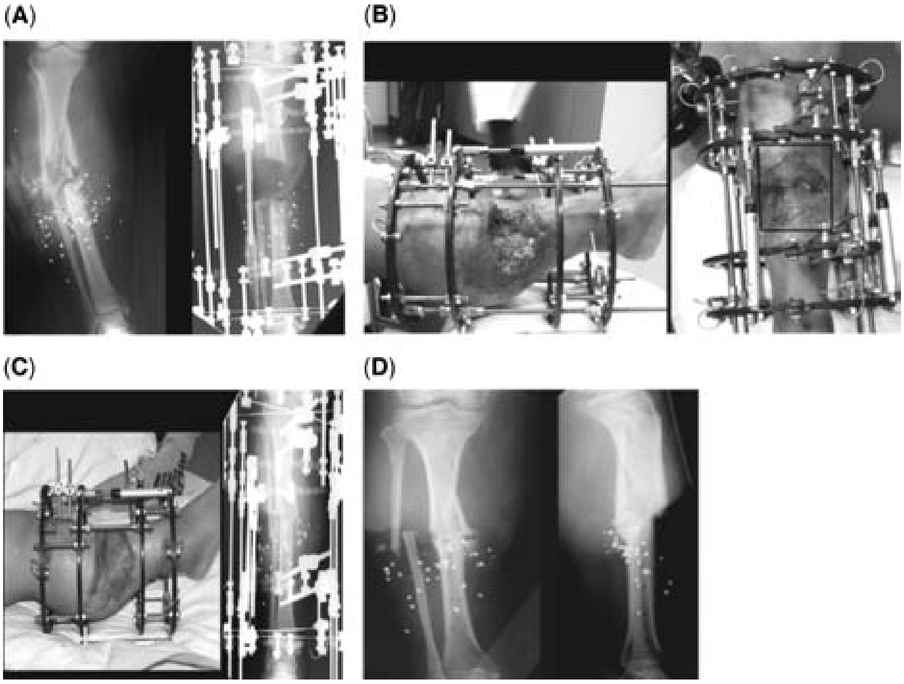

Figure 7 (**A**) Severe gunshot wound with segmental soft-tissue and bone loss. Patient had a one vessel limb as well as severe uncontrolled diabetes and heavy smoking history. (**B**) Gradual shortening at the rate of 0.5 cm/day was undertaken once healthy bone was resected back under soft tissues. As shortening progresses, bone is covered with healthy tissue (box). (**C**) After docking, the soft tissues were skin grafted. (**D**) Follow-up X rays at one-year post frame removal.

distraction/lengthening to maintain the length of the limb. A ring block is applied on either side of the bone defect. Another ring block is placed on the other side of the anticipated lengthening osteotomy site. Rods or struts are applied across this segment and are set up for lengthening or distraction. The rods are then disconnected in preparation for the osteotomy. The osteotomy is done in a percutaneous fashion using either the multiple drill hole and osteotome technique or the Gigli saw technique. Care is taken to perform this osteotomy outside the zone of injury in healthy bone. Ideally, this osteotomy is done in the metaphyseal bone. The proximal metaphyseal location is preferable to the distal metaphysis because of increased bone regeneration potential (Fig. 9).

Trifocal Approach

This is called trifocal because there are three segments with activity. One segment (the defect) is undergoing compression/shortening, and two segments of bony regenerate are undergoing distraction/lengthening. This can maintain the length of the limb. Rings are placed on either side of the defect. Additional rings are placed around what will be two lengthening sites. If the defect is in the middle of the tibia, two osteotomies are performed—one in the proximal and one in the distal tibia (Figs. 10 and 11). Two intercalary bone segments are transported toward each other (Fig. 10). If the defect is in the proximal or distal tibia, another trifocal option exists where two intercalary segments are transported in the same direction (not shown in Fig. 10).

Ilizarov Frame Considerations

The frame should be applied to the leg so that rings are perpendicular to the tibial axis, the rods are parallel to the bone axis, and there is adequate clearance between the soft tissues and the rings, especially at the posterior leg. The bone defect edges should be perfectly pointed toward each other to avoid deformity and to optimize contact at the anticipated

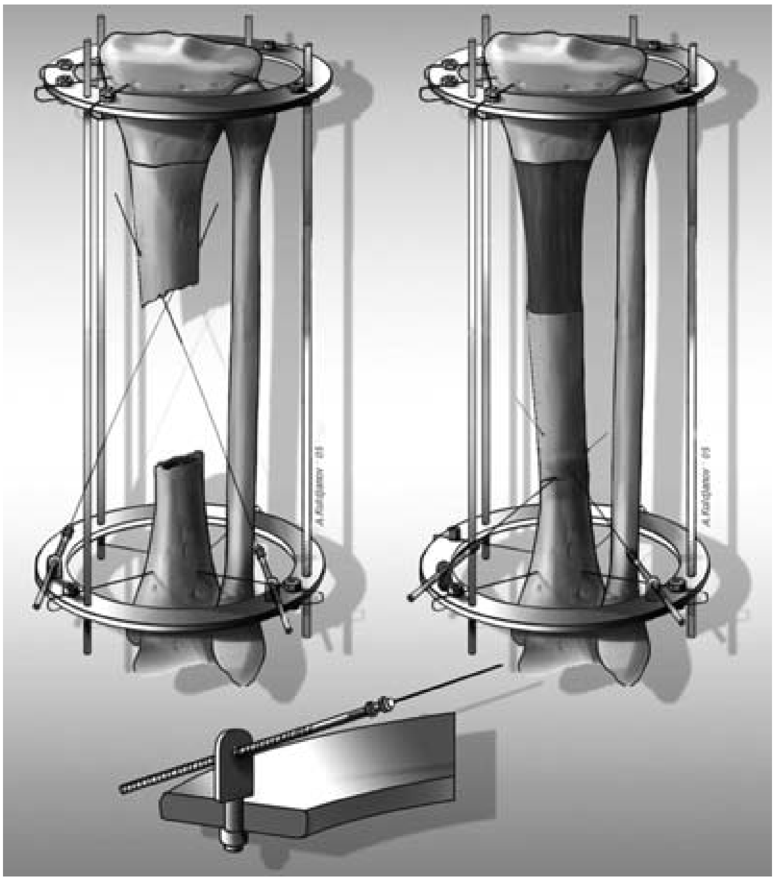

Figure 8 Traction wire transport using longitudinal wires. This methodology requires the threaded rod attachment to be connected to a hinged mechanism as transport proceeds.

docking site. If deformity should occur, this can be managed with frame modification and/or a surgical procedure to optimize contact at the docking site.

Taylor Spatial Frame Considerations

Rings are placed on either side of the defect site and the anticipated lengthening site(s). The rings can be placed independently to optimally fit the leg. This is called the rings first method. One ring is chosen as the reference ring for each level of movement, and it is important that this ring be placed orthogonal to the axis of the tibia. Mounting parameters are defined by the center of the reference ring, and this will define the point in space where the deformity correction will occur (Fig. 11). It is important to maintain enough distance between rings so that the struts can fit properly. In this frame, one is limited by the shortest length of strut. The advantages of this frame are that the application is easier, and the fit on the leg is better when using the rings first method. Also, residual deformity at the lengthening and docking sites can be addressed by using the same frame to correct angulation and translation simultaneously in the coronal, sagittal, and axial planes, without major frame modification. This allows precise docking with optimal bone contact and minimizes angular deformity at the docking and lengthening sites.

Fibular transport has been described for the treatment of massive tibial defects. Commonly, this involves the transport of the entire fibula transversely into the tibial defect. Precise frame orientation must be assured such that the fibula correctly "docks" at either end of the defect. A variation of fibular transfer is the split fibular transfer. The fibula is cut in the sagittal plane, accomplished through small lateral incisions. The medial half of the fibula is then transported into

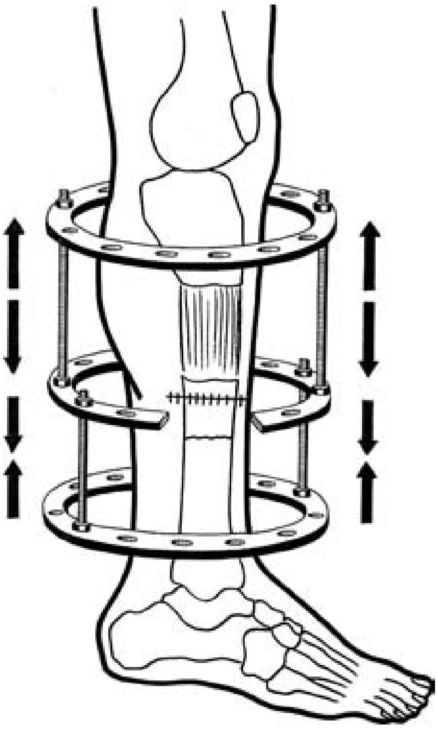

Figure 9 Schematic representation of bifocal treatment depicting gradual closure of bone and soft-tissue defect with bone transport. While there is shortening across the defect, there is simultaneous lengthening through a proximal tibial osteotomy. This maintains the length of the limb.

the tibial defect via multiple olive wires. Olive wires are inserted into the fibula through 2-mm holes drilled in the lateral cortex of the fibula. The wires are then advanced out of the medial cortex of the fibula and attached to slotted, threaded rods linked to swivels on a medial tibial connecting plate. Because tension is placed on the wires, the olives will abut the medial fibular cortex and gradually transport that segment, leaving the lateral fibula intact (Fig. 12).

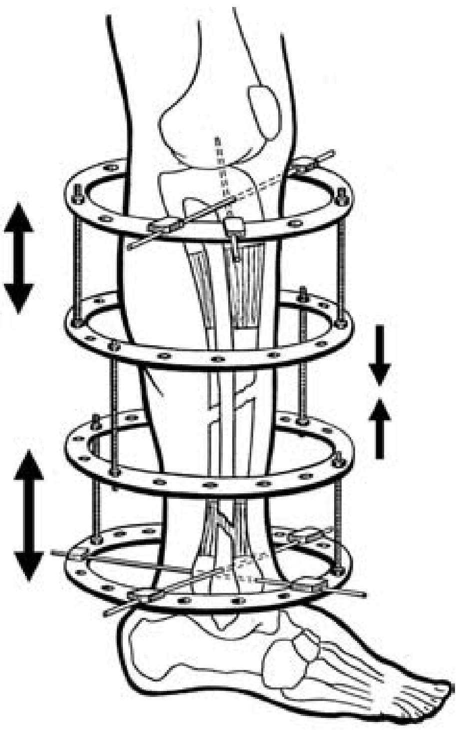

Figure 10 Schematic representation of trifocal treatment. Here, there are three foci of dynamic activity. There is gradual closure (shortening) across the defect and simultaneous lengthening (transport) through two osteotomies of the tibia. This maintains the length of the limb.

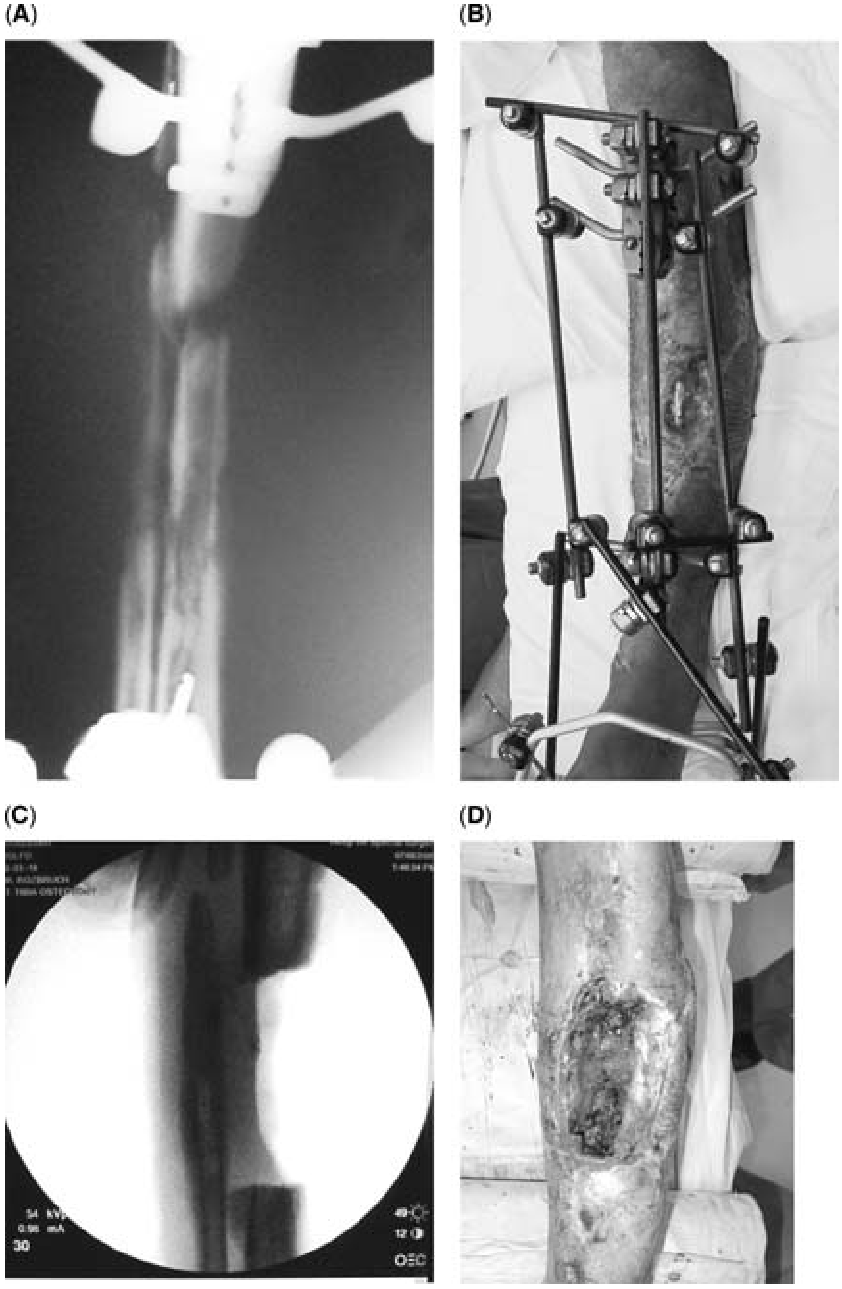

Figure 11 Clinical case example of trifocal bone transport. (**A**) Anteroposterior radiograph of an infected tibial nonunion one year following a pedestrian versus motor vehicle bumper crush injury, which was a Gustilo Anderson grade IIIC open fracture. (**B**) Clinical appearance of this infected tibial nonunion. Previous free flaps were performed and exposed desiccated bone was present. Subsequent operative cultures grew methicillin-resistant *Staphylococcus aureus*, *Pseudomonas aeruginosa*, and *Klebsiella pneumoniae*. (**C**) Lateral intraoperative radiograph following resection of dead, infected bone showing an 11 cm defect. (**D**) Intraoperative appearance of leg following wound debridement and bone resection showing a 13×8 cm soft-tissue defect. (**E**) Leg with Ilizarov/Taylor Spatial Frame in place. This frame has struts across the middle defect and rods across the proximal and distal tibial lengthening sites. There is a vacuum-assisted closure device covering the wound. There is extension of the frame across the ankle for treatment of an ankle equines contracture. (**F**) Interim appearance during gradual closure of the wound. Complete closure occurred after 23 weeks. (**G**) Standing side view at seven months postoperative. (**H** and **I**) Anteroposterior and lateral radiographs of the leg at seven months showing excellent alignment, closure of the defect, and partial bony healing of the docking site, and the proximal and distal tibial lengthening regenerate sites. (**J**) Standing front view three months following frame removal. Total time in frame was 53 weeks. (**K** and **L**) Anteroposterior and lateral radiographs of the leg at three months following frame removal.

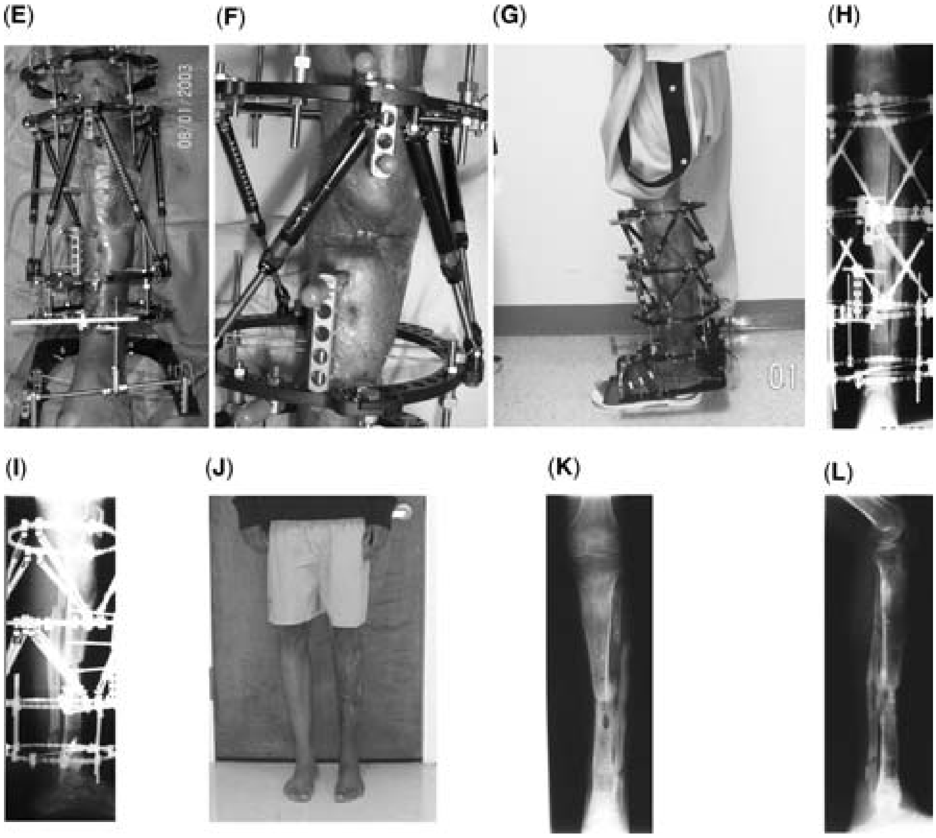

Figure 11 (*Continued*)

TRANSPORT MANAGEMENT

A latency period of 7 to 10 days following corticotomy is allowed prior to initiation of transport. Following corticotomy, auto distractors or threaded distractors are attached between the proximal fixation block and the transport ring. The distractors function as transport motors and the longitudinal threaded rods are utilized as a guide track (Fig. 4). The initial rate of distraction begins at approximately 0.25 to 0.5 mm per day. A slower distraction rate is initially undertaken because of the wide variability of the injury patterns and in the vascularity of the limb. In more extensive fractures or nonunions with a wide zone of injury, transport should be initiated very slowly. When regenerate bone is visualized at approximately two to three weeks postcorticotomy, the distraction rate can be modulated depending on the adequacy of the regenerate bone seen. In general, transport in the acute situation proceeds at a slower rate of 0.5 to 0.75 mm per day as opposed to the standard rate of 1 mm per day.

DOCKING SITE MANAGEMENT

Bone transport is continued until the antibiotic beads have been compressed to approximately the width of one bead. At this time, the patient is returned to surgery and the docking site exposed with removal of antibiotic beads. A high-speed burr is used to freshen the docking site and any irregular areas of bone-contoured flush to ensure maximal cortical contact and stability once docking occurs (Fig. 4). Autogenous iliac crest grafts, as well as numerous alloplastic and recombinant materials, have been used to augment and aid in the rapid consolidation of the docking site. Docking site augmentation has been shown to decrease the overall rate of nonunion and decrease frame time (2,4,7–9,13,15,17,22,23,25). Distal transport is continued within 24 hours of grafting, and the site is compressed once docking has occurred.

During the consolidation phase, compression is maintained at the docking site by compressing the transport ring 0.25 mm every other day until the docking site is radiographically

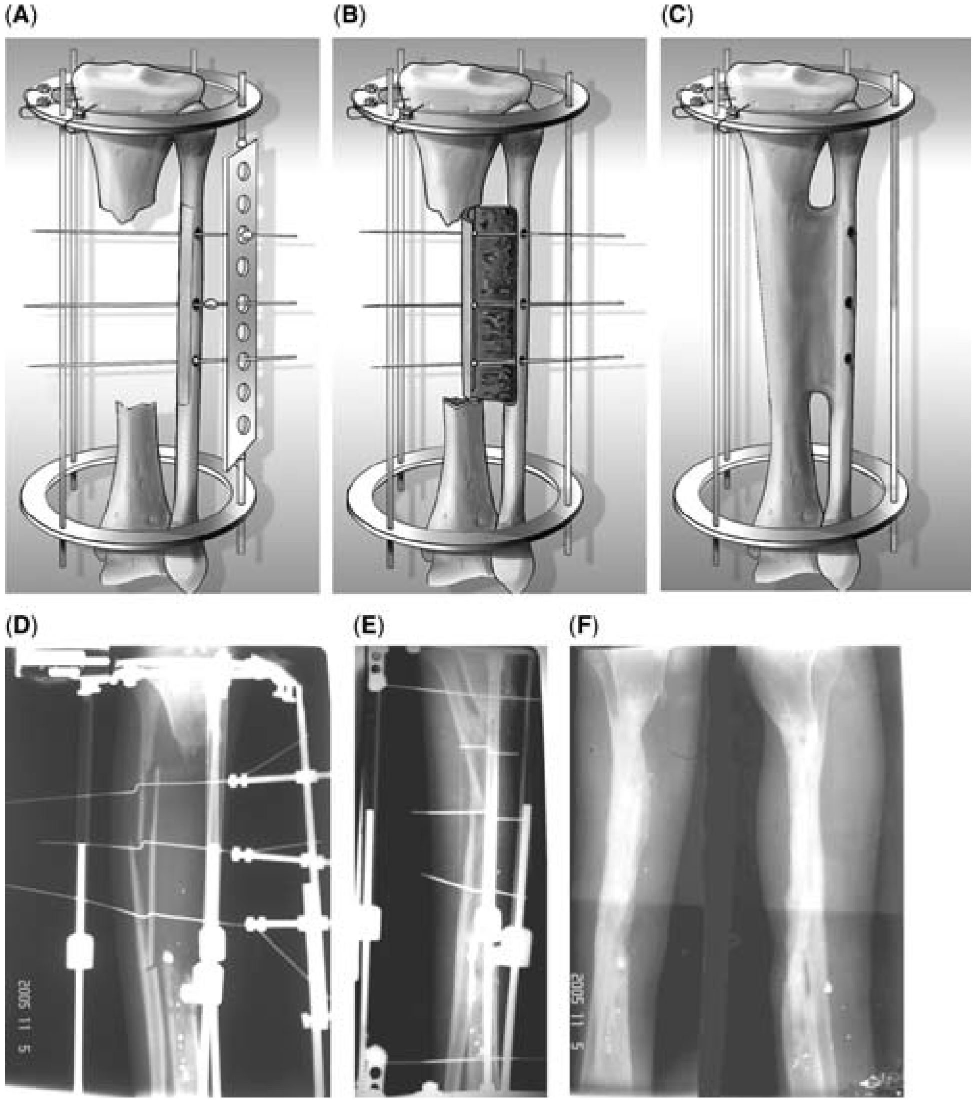

Figure 12 (**A**–**C**) Hemifibular transport using olive wires to transport the medial fibula. (**D**–**F**) Medial half of fibula transported with angled wires. Incomplete fibular corticotomy deformed intact fibula but still allowed complete transfer and docking.

healed. In cases of extremely long transports, the docking site usually heals long before consolidation of regenerate occurs. Frame removal should not occur until the regenerate has matured. Electrical stimulation, as well as ultrasound, has been used with encouraging results to help speed the consolidation of these very extensive regenerate segments (25). Frame removal requires the development of a neocortex, visualized on at least three of four cortices on the AP and lateral radiographs. Prior to frame removal, the frame is dynamized, allowing the transport rings to "float" on the longitudinal threaded guide rods.

COMPLICATIONS

The most common complication is nonunion of the docking site. Numerous authors have demonstrated many successful secondary procedures to manage docking site failure. Of prime importance is the period (time from frame removal to secondary procedure) prior to the undertaking of secondary procedures (6,13,22,23). It is crucial to ensure that contaminated pin tracts heal, and no additional pin site pathology is noted. Delay periods of at least one

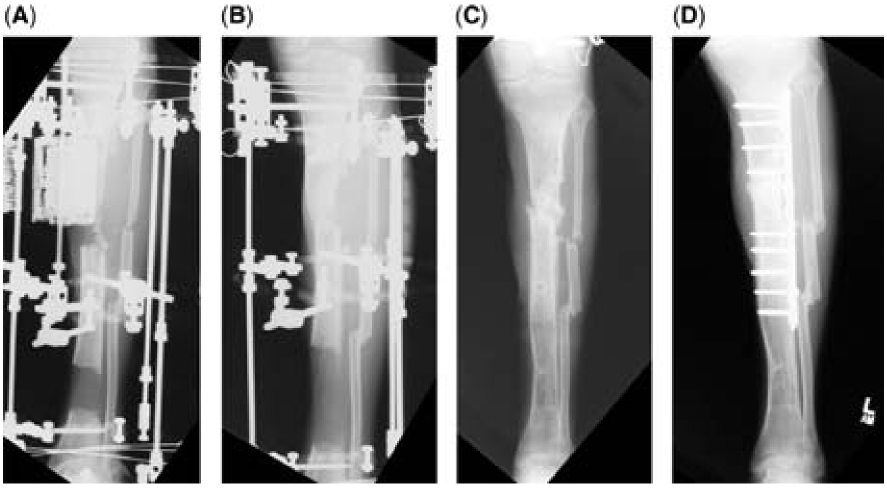

Figure 13 (**A**–**D**) Long retrograde transport under free flap. Despite grafting docking site, progressive nonunion of docking site resulted following frame removal. Nonunion was initially treated with an orthotic, and following a latency period of four months, open reduction internal fixation (ORIF) with bone morphogenic protein (BMP) augmentation resulted in complete healing.

month prior to revision IM nailing or plating should be strictly adhered to. Delayed procedures following frame removal have been shown to result in high rates of union and low rates of infection for the treatment of docking site nonunion (Fig. 13) (6,22,23).

Inadequate regenerate is a concern, especially in cases of extremely long transports. Late deformation and regenerate collapse can occur and the treatment of these complications is very problematic and thus it is best to avoid them at all costs. Modulation of the distraction rate aids in the development of a competent regenerate. Adjuvant modalities, such as ultrasound and electrical stimulation, also assist in the development of a viable regenerate (25). Thorough radiographic evaluation, including computed tomography scan, should be obtained if there is any doubt with regard to the adequacy of regenerate bone. In a few instances, autogenous grafting may assist in the consolidation of a marginal regenerate. One should adhere to the caveat that it is much easier to treat an inadequate docking site (nonunion) than it is to treat an inadequate regenerate (deformation, collapse, recurrent deformity, etc.).

FUTURE DIRECTIONS

Bone transport is a reliable and successful technique; however, it is laborious, requires extreme patient compliance, and has a relatively high rate of complications. With the advancement in external fixator technology, newer frame configurations have simplified the mechanics of frame mounting and transport. The Taylor Spatial Frame[â] (Smith & Nephew, Memphis, Tennessee, U.S.), other hexapod frames, as well as many monolateral transport constructs have devised less complex frame mountings that allow for simplistic application. These frames permit constant adjustment of the proposed docking site without the malalignment potential that

Authors	Journal; year	Title	Patient number	Results	Conclusions
Cattaneo R, Catagni M, Johnson EE (4)	Clin Orthop Relat Res 1992	The treatment of infected nonunions and segmental defects of the tibia by the methods of Ilizarov	28	Functional results were good to excellent in 21, fair in six, and poor in one	Hemicircumferential corticotomy and partial bone fragment internal transport useful for partial defects

(*Continued*)

REVIEW OF LITERATURE (*Continued*)

Authors	Journal; year	Title	Patient number	Results	Conclusions
Green SA, Jackson JM, Wall DM, Marinow H, Ishkanian J (23)	Clin Orthop Relat Res 1992	Management of segmental defects by the Ilizarov intercalary bone transport method	17	All but one patient eventually healed, five bone grafts at docking site, one at regenerate.	Complications: prolonged time in frame. Need to graft docking sites
Raschke MJ, Mann JW, Oedekoven G, Claudi BF (26)	Clin Orthop Relat Res 1992	Segmental transport after unreamed intramedullary (IM) nailing. Preliminary report of a "Monorail" system	20 patients; 13 tibia, 7 femur	Three patients. residual leg-length discrepancies, one hypertrophic nonunion, two deep infections,	Successful use of transport over IM rod decrease time in ex-fix frame
Marsh JL, Prokuski L, Biermann JS (10)	Clin Orthop Relat Res 1994	Chronic infected tibial nonunions with bone loss. Conventional techniques versus bone transport	25	Similar rates of healing; residual infection; treatment time; final angulation; complications and procedures	Unilateral transport device can be successful. Distraction techniques have lower rate of residual leg length discrepancy (LLD)
Lowenberg DW, Feibel RJ, Louie KW, Eshima I (15)	Clin Orthop Relat Res 1996	Combined muscle flap and Ilizarov reconstruction for bone and soft-tissue defects	36	Union and absence of infection were achieved in 35 of 36 patients	Combined approach provides competent biology for grafting of docking site and permits the accurate restoration of limb length
Polyzois D, Papachristou G, Kotsiopoulos K, Plessas S (21)	Acta Orthop Scand Suppl 1997	Treatment of tibial and femoral bone loss by distraction osteogenesis. Experience in 28 infected and 14 clean cases.	42	Infection eradicated in all patients with septic defects. four patients. required grafting at docking site	Radical debridement necessary; grafting of docking site reduces rates of nonunion
Paley D, Maar DC (17)	J Orthop Trauma 2000	Ilizarov bone transport treatment for tibial defects	19	12 excellent, six good, one poor	Extended treatment time, graft docking site
Song HR, Kale A, Park HB, et al.(1)	J Orthop Trauma 2003	Bone transport vs. vascularized fibula for femoral bone defects	37patients; 17 fibular graft, 20 transport pts	Improved outcome for transport patients	Complete debridement of infection required; bone grafting at the docking site
Mahaluxmivala J, Nadarajah R, Allen PW, Hill RA (16)	Injury 2005	Ilizarov external fixator: acute shortening and lengthening versus bone transport in the management of tibial nonunions	18	All healed. union at 12.1 mo shortening and lengthening, 17.2 mo Transport. 8 mo stabilization only	Transport group required grafting at docking sites; acute shortening of 4.6 cm
Beals RK, Bryant RE (7)	Clin Orthop Relat Res 2005	The treatment of chronic open osteomyelitis of the tibia in adults	30	Two patients residual drainage, one patient with aseptic	Advantages of circular frame, bone transport, bone graft, and long-term antibiotics

(*Continued*)

REVIEW OF LITERATURE (*Continued*)

Authors	Journal; year	Title	Patient number	Results	Conclusions
				nonunion	
Rozbruch SR, Weitzman A, Watson JT, Freudigman P, Katz HV, Ilizarov S (27)	J Orthop Trauma. 2006	Simultaneous treatment of tibial bone and soft-tissue defects with the Ilizarov method	25	Bony union in 96%, time in frame 43 wk, lengthening 5.6 cm, LLD 1.2 cm, all wounds closed, no osteomyelitis,	This limb salvage method can be used without need for flap coverage; trifocal approach should be considered for large bone defects

can occur with traditional circular frame constructs. Development of HA (hydroxy-appetite) -coated pins and other substrate biomaterials have improved the pin/bone interface such that these frames may remain on patients for extended periods of time without pin loosening or infection, decreasing the need for rigorous pin care regimes. It is hoped that continued advancement in pin and frame design will overcome the current limitations of prolonged external fixation with respect to patient compliance managing complex frame adjustments. Advancements in IM designs may eventually decrease the need for external transport devices.

The emergence of orthobiologics holds great promise for large skeletal transports. The ability to augment large regenerate segments with percutaneously applied growth factor adjuvants to reduce prolonged consolidation times is an attractive alternative to spending 1.5 to 2 years in a transport device. Similarly, some of these same materials are currently being used to augment docking site union with early good results (8,13,15,17,23,25). Ideally, the ability to rapidly distract a transport segment with a simplistic fixator construct, followed by percutaneous application of docking and regenerate site enhancements to allow rapid consolidation and frame removal, is the ultimate goal.

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