The Evolution of the Ilizarov Technique
Part 2: The Principles of Distraction Osteosynthesis

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Abstract

The history of limb-lengthening surgery can be traced back to the 19th Century. Since that time, the orthopaedic community has made tremendous progress in performing successful lengthening procedures. Among the important contributors to the field is Dr. Gavril Ilizarov. Because of advancements over the past century, limb lengthening has become a viable method of treating severe bony deformities and defects. This article, the second of a two-part series, reviews the principles of distraction osteosynthesis, including a thorough discussion of indications, instrumentation, and surgical technique.

Since Ilizarov, significant strides have been made in furthering the understanding of the biology of limb lengthening. Much of this work originated with Ilizarov and was confirmed with further studies across the United States and Europe. It has been found that the ligaments and capsule will stretch under gradual tension to improve joint contractures, while nerves, vessels, and muscle have been shown to stretch by local neogenesis.1 However, considerably more attention has been paid to understanding how distraction affects bone growth.

Distraction osteogenesis is a term used to describe the de novo production of bone between corticotomy surfaces undergoing gradual distraction (Fig. 1). New bone forms by a processes resembling intramembranous ossification.1,2 Within the normal intramembranous ossification, areas of endochondral ossification may also be present.2 Whether these areas of endochondral ossification within the regenerate are normal or not is controversial. Some investigators argue that its occurrence is inherent to the normal process of regenerate formation.3-4 However, Ilizarov and others have argued that its presence is indicative of instability or of localized ischemia.5-8

The site where the transported segment meets the target segment at the end of bone transport is termed the “docking site.”9,10 The tissue of the docking site is histologically different than that which is seen in the regenerate. Endochondral ossification predominates over intramembranous ossification in this region. There is a progressive increase in the quantity of bony tissue seen here with a concomitant decrease and final disappearance of necrotic tissue and hematoma. This region displays a variable quantity of blood vessels. The histological findings at the docking site do not differ significantly from the normal process of secondary consolidation seen in a fracture but appear in a slower manner.2

The direction of consolidation of the regenerate is also a topic of some controversy. Ilizarov and others describe “zone growth.”1,6,7,11 Zone growth argues that the process of regenerate ossification occurs simultaneously in the regions adjacent to the osteotomized surfaces. A physis-like structure ossifies in both the proximal and distal directions from a central growth zone during distraction. The fibrous interzone, a collagen-rich central region, is the last zone to ossify. Under optimal conditions, this growth zone is hardly visible during distraction. During the neutral fixation period following distraction, the central growth zone gradually ossifies. Fibroblast-like cells become metabolically active and secrete collagen. The collagen eventually forms fibers that align parallel to the distraction force. Osteoblast activity results in osteoid and eventually new bone formation. The new bone formation is greatest at the proximal and distal ends of the regenerate.
A second school of thought argues that ossification of the regenerate site progresses in a single direction accompanying the transported segment of bone. This directional growth has only been seen in animal models.

The Corticotomy

One of the core tenets of Ilizarov’s technique is the use of a percutaneous corticotomy that minimizes trauma to the periosteum and preserves the blood supply of the marrow and periosteum. The use of a corticotomy instead of an osteotomy emphasizes the importance of the blood supply to osteogenesis. Both the periosteal and medullary blood supplies can be preserved by cutting only the cortex. Aronson found that by minimally displacing the edges of the corticotomy, the highly elastic spongiosa within the medullary canal can be preserved along with the medullary blood supply. Significant retardation of osteogenesis has been observed in animal studies with damage to the intramedullary nutrient vessels in osteotomized bones. Animals treated by corticotomy with preservation of the nutrient vessel, however, demonstrated a more rapid rate of bone formation.

Ilizarov performed the procedure known as “closed osteoclasis,” whereby wires were placed around the bone and attached to the frame so that tensioning of the wires would produce a three-point bending force and fracture the bone (Fig. 2). Another more common technique involves making a corticotomy by transecting approximately two-thirds of the cortex and completing the corticotomy by osteoclasis produced by rotating the external fixation rings in opposite directions. Others have described inserting the osteotome
into the corticotomy site and rotating it 90° until the remaining cortex fractures. Other techniques described include a complete transverse osteotomy to ensure division of the entire cross section of the bone or connecting multiple drill holes with an osteotome. It is also common to perform the corticotomy with the use of a Gigli saw.

A 1994 animal study demonstrated no histologic, density, or perfusion differences between the regenerate of dogs that underwent corticotomy with osteoclasis and the regenerate of dogs that underwent osteotomy with multiple drill holes.7,12 However, an increased rate of delayed consolidation was noted in the group that underwent osteotomy performed with an oscillating saw. The investigators postulated that this was secondary to thermal necrosis. Yasui found that a transverse osteotomy was as reliable as a corticotomy in rabbits as long as the periosteum was protected.13

Distraction

Prior to the initiation of distraction, Ilizarov advocated for a postoperative waiting period.6 The duration of the latency period required depends on the preoperative regional blood flow1 and the amount of damage done during the corticotomy.3 This period generally lasts 3 to 7 days and allows for neovascularization prior to initiation of distraction.1,11 Ilizarov’s experiments with distraction osteogenesis made it clear that both rate and rhythm of distraction affect the quality of the regenerate.5,7,14 Ilizarov performed his experiments in canine tibiae. He found that 0.5 mm of distraction per day often resulted in premature consolidation of the regenerate, while 2 mm of distraction per day produced a poor regenerate often with intervening fibrous tissue.6,15 Distraction of 0.25 mm carried out 4 times per day produced an excellent regenerate and allowed organization of early mesenchymal growth into parallel bundles of collagen (Fig. 3). However, he found that the results were further enhanced when distraction was carried out with an autodistractor that broke the millimeter daily lengthening into 60 equal steps. The distraction period proceeds until the desired length of gap formation is obtained. Collagen bundles begin to undergo mineralization from both corticotomy sites towards the center.19,10 As long as distraction is continued, the central region remains fibrous, allowing for viscoelastic lengthening. Mineralization initially protects through the entire cross section of the gap. At the completion of distraction, this solid cylinder of new bone remolds into cortex and medullary canal.

Transformational Osteogenesis

Ilizarov also described the technique of transformation osteogenesis, which involves the mechanical stimulation of pathologic bony interfaces through variations in compression and distraction to induce osteogenesis and regenerate normal bony continuity.6,10,16 He recommended this technique for the treatment of nonunions. Transformational osteogenesis is less well documented histologically than distraction osteogenesis. Success of the technique is dependent on the stability and composition of the pathologic interface. Ilizarov argued that a stiff, fibrous nonunion should be treated with initial distraction.16 Tension is applied across the nonunion site using the Ilizarov device to induce distraction neogenesis. Once new bone formation is visualized radiographically, the bone ends can then be compressed to transform the osteogenic bridge into a solid cylinder of bone.1,16

Transformational osteogenesis can be used similarly to treat a site of mobile pseudoarthrosis. The site must first be compressed progressively at a rate of 1 mm per day for 10 to 15 days.16 Compressive forces induce local necrosis and subsequent neovascularization of the cartilaginous interface. When local resorption occurs, distraction of the site then renews osteoneogenesis. Following the induction of local osteogenesis, compression can then be reapplied to successfully unite the bone ends.

Internal bone transportation requires a combination of distraction osteogenesis and transformational osteogenesis.16,10,11 Internal bone transport is used to manage a large defect within the diaphyseal bone by transporting a metadiaphyseal fragment across the gap. The transported fragment is created by a corticotomy. Using a series of external fixation rings, the proximal and distal ends of the bone are maintained in a stable, fixed alignment. A central ring is connected to
the bone fragment and is used to transport the fragment axially across the intercalary defect. The trailing edge of this fragment undergoes distraction osteogenesis, while the leading edge of the fragment undergoes transformational osteogenesis when it contacts the target bone surface.

Biomechanics
The biomechanical goals of external fixation in bone transport are threefold: to maintain the bone ends in stable alignment, to control the movement of the bone projectile, and to allow compression of the bone in the target zone. Stable fixation of the bone fragments is one of the most important principles in the Ilizarov technique. A stable frame permits full weightbearing, does not restrict the function of adjacent joints, and permits physiologic function of the entire limb, ensuring optimal mechanical and biologic conditions. Secure fixation limits translational micromotion between bone fragments. Weightbearing and active muscle function enhance local circulation and shortens the period required for osseous callus formation and remodeling.

The degree of stability of the apparatus depends on multiple factors. The number of, and tension on, the wires influences the stability of the construct. In addition, the angles between the wires can affect stability. Optimal stability with two transfixation wires is obtained when the wires are perpendicular to each other. When anatomic and functional constraints prevent perpendicular wire placement, supplementary wires may be required. Stability is also dependent on the number and size of the rings in the apparatus and the rigidity of the fixator construct. The amount of compression or distraction incorporated into the configuration can also contribute to the stability. The shape, cross-sectional area, and the density of the bone fragments, as well as the shape, location, and plane of the fracture or osteotomy relative to the longitudinal axis of the bone are also important determinants of the stability of the construct. Myofascial and ligamentous tissues, along with the vectors of the muscles within the limb, contribute as well.

Inadequate stability can lead to inhibition of union, damage to the local circulation, and the formation of callus through fibrocartilage. It may also lead to patient discomfort, which can reduce functional use and result in altered vascularity, edema, joint stiffness, osteoporosis, and complex regional pain syndrome. Patient discomfort also limits joint motion, decreases weightbearing on the limb, and can result in progressive osteoporosis that may lessen the efficacy of the wire function. Finally, inadequate stability can also increase the likelihood of wire sepsis.

Essential to the stability of Ilizarov’s construct are thin, tensioned wires. These wires form a nonlinear, self-stiffening mechanical structure and provide rigidity against displacement of the bone ends in six degrees of freedom. The wires are pre-tensioned to provide an initial stiffness against displacement perpendicular to the axis of the wire. Rotational and translational displacements about each wire are resisted by coupled forces between adjacent wires within each ring-wire-bone construct. The system is relatively flexible in the axial direction of the long bone, perpendicular to the wires, compared with constructions using larger diameter transfixation pins. Bone displacement causes distortions in the wire geometry, creating reaction forces. When the bone forces and displacements equal the wire forces and displacements, the system reaches a new equilibrium. The wires then act as small springs within the more rigid system of rings and threaded connecting rods.

In bone transport, the bone projectile movement must be carefully controlled. Strains across the osteogenic zone trailing the bone projectile must be controlled though adjustment of both the magnitude and the temporal rate of the movement. The bone projectile must also be moved with a precise orientation so that the cortical surfaces at the target site will be aligned. At the end of the transportation cycle, the target site is then loaded in compression. This will initiate transformational osteogenesis.

The Ilizarov Device
The Ilizarov device is a modular construct consisting of 32 individual pieces that allows for 100s of possible configurations. The wires (1.5 mm and 1.8 mm diameter) are connected to modular rings by connecting bolts and are secured under tensions of 50 to 130 kg. Special stopper, or “olive,” wires have a 4 mm bead welded along the mid-wire. This wire can be used to stabilize the near cortex and can function to dynamically compress fragments or internally transport bone fragments following corticotomy.

Two to four wires are secured to each ring to stabilize each bone fragment. Longer bone fragments may require connecting two rings by threaded rods. After obtaining fixation, bony transport, compression, or distraction can be accomplished by gradual tightening or loosening of threaded connecting rods. The device can then be modified to correct axial, angular, or rotational deformities.

For bone transport, the simplest most commonly used configuration consists of three rings, with one proximal to the corticotomy site, one distal to the zone of the original defect, and one in the transport segment. The fixator can transfer loads around the osteogenic site and provide a reaction point for mechanical forces created during transportation. This construct may be augmented by additional rings to provide additional rotational stability.

Multiple variations exist on this simple construct. One construct employs stopper wires and inclined rods. Stopper wires are essentially obliquely placed olive wires that pierce the bone projectile cortices and are fastened only on one end to inclined threaded rods mounted on a hinged support. The construct essentially “drags” the segment to the target. A minimum of two stopper wires are required to provide stability to the transported bone. Simultaneous rotation of the threaded rod at its pivot point is required to prevent bending of the stopper wire. The stopper wire and threaded...
rod construct essentially function as linearly elastic steel lag screws. If the hinge is left freely mobile, the tension will automatically rotate the threaded rod into proper alignment.

A second variation is known as the “transportation ring.” This commonly used construct employs transosseous pre-tensioned wires through the bone projectile. The ring is advanced along threaded connecting rods. While this configuration is simpler to construct and maintain, there are difficulties with its use. The movement of the transport segment may not mirror the transportation ring movement until the wire forces are equal and opposite to the soft tissue restraining forces. In addition, the transportation ring requires that the tensioned wires cut linear tracts in the skin and underlying soft tissues as the transport proceeds. A variation of this technique is now commonly used which utilizes half-pins in the transport segment for fixation rather than wires.

A “stopper wires and transport ring” construct combines characteristics of both of the constructs. Instead of pivots, the stopper wires are fixed to the transport ring at their initial angle. The ring is then advanced at the desired rate, as the stopper wires “pull” the ring. The stopper wire transport reduces the cutting path of the wires through the soft tissues. However, it requires a more complex maintenance program than any of the other constructs. Moreover, successful transformational osteogenesis may require an additional procedure to exchange a transport ring for the stopper wires in order to achieve adequate compression forces.

Complications

Depending on the criteria used, complication rates have been reported to be anywhere from one to two complications per lengthening. A recent study of patients treated with the Wagner technique found an average of two complications per lengthening, at least one of which was usually serious enough to prevent achieving the original goals of the surgery. With the introduction of more physiologic methods of lengthening pioneered by Ilizarov, bone healing problems have become far less common, severe complications have decreased, and the goals of treatment are now usually achieved. However, the spectrum of potential complications remains the same irrespective of the technique used.

Tension on the muscle is considered to be the principle stimulating mechanism for muscle regeneration under conditions of limb lengthening. However, this tension can result in muscle contractures. They occur usually as a result of tension generated due to distraction, occurring when the muscle length becomes relatively short compared to that of bone. Contractures tend to occur in the over-powering muscle group secondary to an imbalance of strength between the flexors and extensors. The muscles most frequently involved in contracture are those that cross two joints. These muscles tend to have fibers of various lengths while those that cross only one joint tend to have fibers of equal length. This may lead to variations of tension within the same muscle.

Muscle contractures may also occur secondary to transfixation of muscles or tendons by the pins. The risk of occurrence of these types of contractures is increased by the use of transfixation pins instead of wires, increased diameter of the pins, or longitudinal clustering of several pins in the same plane. Transfixation of the tendons and fascia tends to restrict joint motion more than transfixation of muscle.

In order to prevent the occurrence of these contractures, physiotherapy has been recommended. However, stretching exercises do not prevent contractures unless they can be maintained for at least 6 hours per day. Paley suggests that splinting or transfixation across joints is recommended if the patient is felt to be at risk of developing contractures. For patients who have already developed muscle contractures, dynamic splinting may be helpful in stretching out the contracture. If non-operative management fails to correct the problem, several options exist. The bone can be over-distracted to allow for lengthening of the muscle followed by compression. Alternatively, the apparatus can be applied across the joint, and the contracture can be corrected. Finally, tendon lengthening can be considered after removal of the apparatus.

Joint complications, such as subluxation and stiffness, are other possible complications of this procedure. The most common predisposing factor for joint subluxation is preexisting joint instability (most commonly secondary to congenital causes). Imbalanced muscle tension that can develop during lengthening procedures may lead to joint subluxation. The knee is the most susceptible joint secondary to its inherent lack of bony stability. On flexion of the knee, the hamstring muscles can work unopposed to pull the tibia posteriorly on the femoral condyles. This complication, if mild, may be treated with physiotherapy to stretch the deforming muscle force. More commonly, however, treatment of joint subluxation will require the apparatus to be extended across the joint in order to first distract the joint and then reduce it. Joint stiffness is generally a late complication that occurs secondary to persistent muscle contractures or increased pressure on the joint surface during the lengthening. This may be treated by extension of the apparatus across the affected joint and distracting the joint. If this technique is employed, the apparatus must be used to mobilize the joint prior to its removal.

During the lengthening process, there is a tendency for the limb segment being lengthened to gradually veer off its intended course, resulting in axial deviation. The direction of this deviation depends on the bone involved and the level of the osteotomy. Axial deviation may be caused by muscle imbalances or instability secondary to an inadequate construct, loss of tension in the pins, or loosening of the pins. In order to prevent this complication, pins should be placed 5° to 10° inclined to the opposite direction of the expected deviation. If axial deviation does occur, treatment is possible. If there is less than 5° of angulation, the treatment of choice involves over-lengthening the side of the deviation. If the deviation is greater than 5°, the apparatus must be modified. In larger lengthenings, additional olive wires may
be required to pull the bone into the proper position.

Neurologic and vascular injuries may occur with limb lengthening procedures. Neurologic injury may be related to either surgical technique or the distraction itself. Injury related to the surgical technique may occur with pin placement, or it may occur as a stretch injury during the osteoclasis maneuver used to complete the osteotomy. Pin related nerve injuries can best be prevented by a thorough knowledge of the cross sectional anatomy at the level of pin placement as well as the placement of pins in “safe” anatomic planes. A distraction related nerve injury is much less common. Patients will usually report significant discomfort with this type of complication. The first signs of a distraction related nerve injury are hyperesthesia and pain, followed by hypoesthesia, decreased muscle strength, and finally paralysis. Treatment of a distraction related nerve injury includes increased physiotherapy, functional unloading, and decreased weightbearing of the affected limb. It is also possible to slow down or temporarily stop the distraction to allow the nerve injury to resolve.

Vascular injuries may be related either to surgical technique or distraction. Rarely, an arteriovenous fistula can occur secondary to perforation of a vein and an artery at the same time by a pin. Additionally, placement of a pin directly adjacent to a pulsating artery can result in late erosions with pseudo-aneurysm formation. Other vascular-related complications include compartment syndrome and DVTs. Commonly, patients will suffer from edema during lengthening, particularly in patients who are active and walk frequently. Patients must be counseled that it may take several months after the removal of the apparatus for the edema to resolve completely.

Other complications may be related to the rate of consolidation at the distraction site. Failure of the osteotomy site to open after the initiation of distraction is more often secondary to an incomplete osteotomy than true premature consolidation. When true premature consolidation does occur, it is likely to be secondary to an excessive latency period. This allows significant callus healing to block the distraction of the osteotomy site. This complication is most commonly seen in the femur and fibula, and commonly occurs in patients with Ollier’s disease. Premature consolidation may be treated with continued distraction until the consolidated bridge of bone ruptures. This type of treatment results in a rupture that is sudden, unexpected, and painful. Once the consolidated bridge has been ruptured, the patient must back up the distraction by the same number of millimeters that had been applied since the bone consolidated. This technique risks delayed or nonunion. Premature consolidation may also be treated with attempted closed rotational osteoclasis. If these techniques fail to break the consolidated bridge of bone, repeat corticotomy may be required.

In contrast to premature consolidation, delayed consolidation of either the regenerate or the docking site may occur. Rates of delayed consolidation have been reported anywhere from 35% to 68%. This complication may occur secondary to technical factors including a traumatic corticotomy, initial diastasis, or excessively rapid distraction. With regards to the docking site, DeCoster reported that for every day of transport, 2 to 3 days of consolidation are needed at the docking site. Delayed consolidation may also occur secondary to patient factors including infection, malnutrition, or metabolic problems. Delayed consolidation requires identification of the underlying etiology with targeted treatment. Alternating compression and distraction of the moving segment, or the “accordion maneuver,” may be applied if consolidation continues to be delayed.

Pin site problems may also occur. These complications are related to motion at the pin-skin interface, the amount of soft tissue between the skin and bone, and the diameter of the pin used. The risk of pin site problems can be lowered by maintaining adequate wire tension in order to minimize pin-skin and pin-bone motion. In addition, using rubber stops or cubic foam sponges may apply pressure to the skin and stabilize the pin. Pin tract problems always develop from the outside in and careful inspection of the pin sites can provide the practitioners with the first sign of pin tract problems. Problems begin with soft tissue inflammation, progressing to soft-tissue infection, and finally to bone infection. Oral antibiotics may be used to treat soft tissue infections. However, recalcitrant infections, infections around wires that pass through joints, and cellulitis about the pin site may require treatment by removal of the offending wire.

After removal of the apparatus, fracture through the regenerate may occur. This can present as gradual axis deviation of the bone due to incomplete healing, a complete fracture, or buckling of the bone with some loss in length. This can best be avoided by careful analysis of the regenerate bone in the distraction gap prior to removal of the apparatus. The ossifying regenerate should have an even consistency with evidence of neocorticalization and an opaque appearance similar to the surrounding normal bone prior to removal of the apparatus. If regenerate fracture does occur, it may be treated with a cast or with reaplication of the apparatus.

At times, a fracture may occur as an osteoporotic stress fracture. This is a fracture that occurs through an area of normal bone and is secondary to marked osteoporosis. Osteoporosis can occur in these patients secondary to lack of weightbearing, a hypervascular response to distraction, pain, or reflex sympathetic dystrophy. The stress fracture similarly may be treated with either a cast or reaplication of the apparatus.

Pain is an important consideration in the use of the Ilizarov technique. Postoperative pain may be intense for the first few days after the initial operation. Contraction of any muscle transfixed by pins is initially painful but resolves within 1 to 2 weeks. Distraction pain is distinct from post-surgical pain. Distraction pain is more of a chronic, dull aching pain that can be extremely variable in patients. This pain is more common in longer lengthening, double
level lengthening, or fixation or splinting above or below the lengthening segment.\textsuperscript{19} This type of pain is most likely secondary to stretching of muscles and nerves and rarely is severe enough to require narcotic administration.

Psychological complications are also commonplace in patients undergoing limb lengthening by these techniques. Depression is common but usually responds well to temporary anti-depressant medication.\textsuperscript{19} Similarly, patients often report difficulty sleeping, loss of appetite, and unintentional weight loss. All of these psychological complications usually resolve spontaneously within 1 week of stopping the distraction.\textsuperscript{19}

The Use of Distraction Osteogenesis

Distraction osteogenesis has been applied to the treatment of a wide variety of problems including severe limb length discrepancy, acquired and congenital deformities, fracture nonunion, and osteomyelitis.\textsuperscript{14,15,28} Regardless of the reason for use, the general technique remains unchanged: bone division, stable fixation of the fragments, a 7 to 14 day latency period, distraction, consolidation, assessment of regenerate bone, and removal of the frame.\textsuperscript{2,23,28,30,31} Care must be taken to allow for at least 2 to 3 days of consolidation for each day of distraction. Prior to removal of the frame, a careful assessment of the regenerate and docking site, if present, is required.

Similarly, this technique may also be applied in acute limb shortening followed by limb lengthening.\textsuperscript{23,32-34} The theoretical advantage of this technique is that it will allow for faster healing of a traumatic defect as it does not require waiting until docking is achieved to begin callous healing. Shortening assists with the closure of soft tissue defects, though it may result in soft tissue redundancy and swelling.

These techniques can be readily applied to the treatment of various types of nonunions. Atrophic nonunions may be treated with bifocal osteosynthesis, which involves resection of the nonunion site, compression at the nonunion site, and bone lengthening at an osteotomy site remote to the nonunion site.\textsuperscript{28,32} This technique also allows for alignment if deformity is also present.

Hypertrophic nonunions have traditionally been treated by revision to rigid fixation. These fractures have a vital blood supply from each bone end and a dense collagenous interface. These characteristics allow the nonunion to be treated by stimulating bone formation with primary distraction and realignment when necessary.\textsuperscript{36} Nonunions with bone loss can be transported with bone transport or shortening-distraction.\textsuperscript{28,37}

Infected nonunions require resection of the focus of infection, with removal of all necrotic and poorly-vascularized tissues.\textsuperscript{29} The remaining osseous segments must have an adequate blood supply to promote bone formation at its trailing end and healing at its leading end.\textsuperscript{11} Bone transport can then subsequently be used to eliminate the residual defect. When compared to treatment with bone graft, antibiotic beads, and vascularized bone grafts, patients who are treated with bone transport experience similar rates of healing, duration of treatment, final deformity, complication rates, and total number of operative procedures.\textsuperscript{22,24,28,38} However, patients who undergo bone transport have improved limb length discrepancy, decreased cost of treatment, and shorter duration of disability than those treated with bone graft, antibiotic beads, and vascularized bone graft.\textsuperscript{22,28}

The benefits of treating nonunions with bone transport include the ability to achieve regeneration of living bone with the same strength and width as that of native bone.\textsuperscript{28} In addition, this technique can be used to treat very large defects, up to 30 cm, in both children and adults.\textsuperscript{39} Moreover, this technique allows for simultaneous deformity correction as well as allowing for the treatment of concomitant soft tissue problems.

Unfortunately, bone transport is not the answer for all nonunions. Its use requires specialized training and equipment. Frequently, bone transport requires a long treatment duration during which numerous complications may occur. This technique can also be costly. A 1994 cost analysis determined that the cost of limb salvage using the Ilizarov technique was $60,000 compared with $30,000 for an acute amputation, although this does not take into account lifetime prosthetic costs.\textsuperscript{30}

Conclusion

Surgical limb lengthening and bone transportation techniques have undergone significant evolution over the past century. While numerous potential complications continue to exist, most complications are now minor and easily treatable. Distraction osteogenesis has become a viable treatment option when applied in a cooperative patient by a surgeon with appropriate training. Advances in technique continue to be made, and the introduction of new devices has made ring external fixation a more accessible treatment option.

Disclosure Statement

None of the authors have a financial or proprietary interest in the subject matter or materials discussed, including, but not limited to, employment, consultancies, stock ownership, honoraria, and paid expert testimony.

References

5. Li G, Simpson AH, Triffitt JT. The role of chondrocytes in intramembranous and endochondral ossification during
distraction osteogenesis in the rabbit. Calcif Tissue Int. 1999 Apr;64(4):310-7.