Review Article

Lower Extremity Bone Lengthening

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ABSTRACT

Limb lengthening is a useful method of elongation the bones in the arms or legs. This method is carried out gradually and continuously so that bones and soft tissues such as muscles, skin, and nerves can increase in length slowly. Ilizarov's method is the origin of much of the contemporary knowledge of bone elongation. Professor Gavril Ilizarov is the one who developed bone transport (BT) which is one of the applications of DO based on the displacement of bone fragments without limb elongation to treat trauma, non-union, and large bone defects (mechanical effects of segmental bone). Ilizarov's bone transport technique has consistently played an important role in protecting soft tissues and promoting effective functional recovery and rehabilitation of limb length. This article was written to review the history, and current concepts of limb lengthening, biology, and complications.

Keywords: Limb lengthening, Ilizarov's method, limb lengthening device, complications
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INTRODUCTION

Currently, the basic principle of bone elongation is brought down from the general laws of biology tensile tension. Gradually, traction on living tissue produces pressure which is stimulating and guarding the process of regeneration and active growth in that particular tissue. In presence of sufficient blood supply, stable traction of body tissues gradually can activate biosynthetic and proliferative purposes.[1] Process of leg elongation and deformity correction are working based on the technique of distraction osteogenesis. Revolutionary of this surgical principle breaks previous evidence that bone cannot regenerate. Bones can regenerate naturally after a process of rupture, fracture, and purposely cut through surgery (osteotomy). Leg lengthening surgery uses the principle of osteogenesis.[2,3]

Over the past 35 years, orthopedics specialists have made three great advances in leg elongation procedures: "impaired osteogenesis" mediated by Gavriil Ilizarov's method and circular fixators which can easily adapt indefinitely with the fixation on fine wire bone fragments.

Indications for leg lengthening are not generally clear. A few years ago, bone elongation has been conducted not only for bone deformity caused by trauma, the treatment of dwarfism, congenital abnormalities, tumors, and infections, and for aesthetics.[2] Leg lengthening surgery has a high success rate of around 95%. The resulting scar tissue is usually minimal as only a small incision is required in most techniques.[3] Although some minor clinical manifestations may occur such as tingling and stiffness in the joints, severe complications are rare with leg lengthening surgery. Serious complications usually occur in patients who are at high risk, such as patients being treated for limb salvage.[4]

HISTORY

The first person who implement skeletal traction for bone elongation was Alessandro Codivilla of Bologna. He used acute elongation forcibly for short distances under the influence of narcotic drugs. Alessandro Codivilla suggests another procedure for greater distances with sustainable lengthening, this method uses disturbance with an oblique osteotomy and calcaneus pins, followed by 25-30 kg of traction. Subsequent elongation is accomplished by implementing more traction gradually. In 1932, Abbott published some of his experiences performing lower extremity elongation of 73 subjects (45 patients of tibial lengthening) at the Shriners Hospital for Children with Disabilities in St. Louis. The review mentioned traction and anti-traction techniques where continuous traction is sluggish to resolve soft tissue resistance, accurate contact, and alignment of the bony edges.[1,2]

Ilizarov's method is the origin of much of the contemporary knowledge of bone elongation. In 1951, Ilizarov began his work on treating patients with spinal deformities using transfixion-tensioned wires and circular frames. Subsequently, Ilizarov has found the law of biological tensile stress or histogenesis disorder and implemented the method for treating various conditions like bone defects, osteomyelitis, non-union, dwarfism, multiple bone tumors, congenital deformities, shortening of bones, and fractures.[4,5]

From the early 1970s to the mid of 1980s, Heinz Wagner from Nurnberg, Germany reached the international championship in limb elongation and reconstruction of limb deformities. The technique proposed by Wagner is gaining increasing popularity in Europe and the United States; This procedure consists of 3 types of operations. The first surgery was diaphyseal osteotomy and unilateral external fixation implantation. No time to wait,
5 mm elongation is performed during acute surgery, followed by 1.5 mm daily distraction. The second step of this operation is bone grafting and plating. The last step of the operation is removing the plate and casting. There is a high complication rate with this procedure.[2,5]

Taylor Spatial Frame is known as a popular modality of hexapod computer-aided circular frames. The implementation of self-directed motorized nails to avoid and reduce external fixation complications and obtain rehabilitation rapidly. Currently, the Ilizarov method is still the basis of all bone elongation principles.[1,2]

INDICATION OF BONE LENGTHENING

Indications for limb lengthening are generally unclear.[1] In the last century, the indications for leg lengthening have changed from leg length deformities and discrepancies caused by osteomyelitis, poliomyelitis, malunited fractures, war injury, congenital disorders like simple femoral hypoplasia, femoral deficiency, tibial aplasia, fibular hemimelia, hemihyper and hemihypo-trophy, and other problems acquired, like post-traumatic growth arrest, avascular necrosis, post-infectious

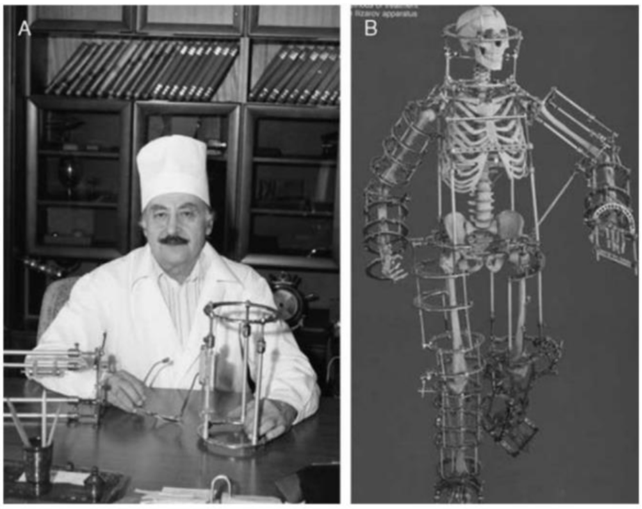

Figure 1. Professor Gavriil Lilizarov instantiates cross tension using circular wire known as Ilizarov Man in Glastnost 1990s for bone fixator

problems, Perthes disease, bone dysplasia, rickets, Blount disease, enchondromatosis, Ollier disease, and others. In addition, aesthetics can be an indication of leg lengthening.[5] Leg lengthening for cosmetic reasons uses the Ilizarov principles with circular external fixation has been implemented individually with constitutional short stature to be taller than before. This procedure is referred to as cosmetic leg elongation or symmetrical limb elongation and has been compared to the simplest plastic surgery options. All patients should undergo a psychiatric examination to rule out body dysmorphic disorder. In addition, all patients are required to own a detailed preoperative psychological analysis to get rid of psychiatric illnesses that may influence the patient's ability to create sound decisions.[6,7]

Classical knowledge classifies shortening of the limbs into 3 parts, namely < 2 cm (can be excused); 2–4 cm (possibly elongation); and > 4 cm (elongation is required to avoid complications of lower leg length inequality like scoliosis and hip tilt.[6] In addition, a difference of approximately 5 cm in length between the legs can be handled with epiphysiodesis on the increasing leg or decreasing the longer leg at appropriate times.[7] There are no factors that influence the setting of the group. Limb elongation has a significant role to decide the treatment. The causes of decreasing bone length and deformity play a great role in planning.[8] The etiology can be congenital insufficiencies like old poliomyelitis, congenital tibial hemimelia or short femur, bone excrescence similar to heritable multiple exostoses, fibular hemimelia, or once trauma. In achondroplasia cases that lead to dwarfism, the bilateral extension results in genu varum.[7,8]

BONE LENGTHENING TECHNIQUES

Biology of bone lengthening

The biological process of bone elongation has 3 stages: a latent phase, a distraction phase, and a consolidation phase. The latency phase results in a response similar to the initial trauma. This phase begins immediately after the transverse osteotomy procedure and extends to the onset of distraction. All processes that occur during this phase are essentially the same as those that occur in the early stages of fracture repair. The recommended latency time is about 7-14 days between surgery and the onset of the problem.[3,6,9] The length of the latency chosen depends on the age of the patient, the site of lengthening, the underlying disease, and diagnosis. The local trauma of osteotomy induces an inflammatory response causing the release of cytokines, IL-1, IL-6), leading to the recruitment, proliferation, and differentiation of mesenchymal stem cells from bone marrow, periosteum, and endosteum. These cells produce a variety of growth factors (GF) including bone morphogenetic proteins (BMPs, notably BMP-2, BMP-4, and BMP-6), transforming growth factor b (TGF-b), platelet-derived growth factor (PDGF), and insulin-like growth factor (IGF-1). The hematoma formed in the osteotomy gap and its immediate surroundings will be inhabited by fibroblasts, chondroblasts, and osteoblasts. In fracture repair, bone formation proceeds through callus formation, the bone being formed mostly through endochondral bone formation when there is some instability across the fracture site, and mostly through intramembranous bone formation when there is a more stable fixation across a minimal fracture gap.

During the period of distraction, the pull force is implemented on the callus with a certain rhythm and speed using a distraction tool. External fixators are used in this technique as intended for low stress. Aronson has described the morphological and histological changes that occur in disturbed fissures using longitudinal tensile forces.[9,10] The central fibrous zone or fibrous interzone (FIZ) is formed when the primitive callus is stretched. The area is rich in cells such as chondrocytes, oval cells, and fibroblasts which are morphologically intermediate between fibroblasts and chondrocytes. In the fibrous interzone, some osteoblasts differentiate and deposit osteoid along the collagen bundles. Next, the osteoblasts crystallize the minerals parallel to the collagen bundles and form a zone known as the micro-column formation zone (MCF). The microcolumns are shaped similarly to stalagmites and stalactites and have been described as cones measuring 150-200 m.[10,11] Mineralization proceeds well along the collagen bundles longitudinally, parallel to the distraction force, and more cross-sectional collagen fibers are joined. Between the fibrous interzone and the microcolumn formation zone, there is a cell zone that has a high growth rate. This zone is called the primary mineralized front (PMF). Once the desired bone length has been reached and disruption has ceased, it enters the initial phase of consolidation, a phase in which bone and large amounts of osteoid undergo remodeling and mineralization.[6,12]

During the consolidation phase, bone regeneration begins to consolidate and bone remodeling occurs until the cortico-medullary structure architecture reaches its normal limit and can withstand the full load without protection.[11] The regenerated bone features a central unmineralized zone, neighboring zones of mineralizing tissue, and peripheral zones consisting of woven bone already influenced by the remodeling processes. As the central parts of the regeneration evolve into bone, the growth factors peaking during the distraction phase are downregulated, and remodeling takes over. PTH and the Wnt signaling pathways are important in this phase. The RANK/OPG ratio decreases and TNF-a is upregulated. Intermittent mechanical stimulation is likely to play a role in maintaining the bone mass of the regenerated bone during this phase of active remodeling, underscoring the importance of keeping patients mobile and weight-bearing. Vascularity is a very important component: blood flow is not only increased in bone formation but also in remote areas of the same bone area. Bone remodeling includes endochondral ossification and trans chondroid bone formation.[13] Enchondral ossification can be identified by the transition of cartilage from fibrous tissue to bone. it is usually seen at the junction of FIZ or newly mineralized membranous bone originating at the ends of the cut.[10,14] Chondroidal bone is formed directly by chondrocyte-like cells during trans-chondroid ossification, with a gradual shift from fibrous tissue to bone (chondroid bone).[13]

SURGICAL TECHNIQUES

Codivilla in 1905 described limb lengthening using the distraction osteogenesis (DO) technique for the first time. This technique was not accepted in the general population until Ilizarov initiated the identification of the physiological and mechanical factors responsible for regulating successful bone regeneration during the DO technique.

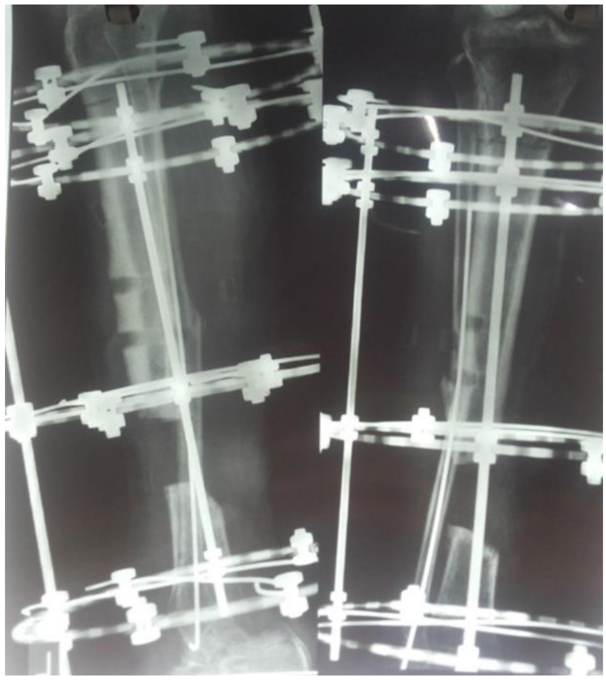

Figure 2. Illizarov methods at Soeharso Orthopedic Hospital Surakarta

In experimental and clinical studies conducted by Ilizarov, the DO method has been used clinically as a method to enhance bone regeneration in orthopedic disorders and more extensive oral/maxillofacial disorders. During the DO technique, the tissue will experience a relatively stable and constant tension and become metabolically active. The process of new bone formation occurs along the line of distraction stress in the disturbed segment of both extremities, at the cut ends of the two bone segments.[14,16] Rejuvenescence of the osteogenesis process is influenced by two factors which are tissue factors and prior internal fixation.[17] Some techniques can lead to osteogenesis disturbance such as internal bone transport (IBT), simple lengthening, and acute shortening and re-lengthening (ASRL). for nonunion cases or shortening limb without bone damage, the simple lengthening technique can be used. In nonunion cases with bone defects, internal fixation or the ASRL approach can be done. The size of the bone defect determines the choice of approach. More than 4 cm defect needs bone transport while less than that can be done with the ASRL approach.[18]

BONE TRANSPORT

Professor Gavril Ilizarov is the one who developed bone transport (BT). The DO procedure separated two segments in the new bone as induction. Bone transport (BT) is one of the applications of DO based on the displacement of bone fragments without limb elongation to treat trauma, non-union, and large bone defects (mechanical effects of segmental bone). Ilizarov's bone transport technique has consistently played an important role in protecting soft tissues and promoting effective functional recovery and rehabilitation of limb length.[19]

This defect is most typically seen within the lower extremities, particularly within the femur and tibia. Corticotomy performed at low energy to treat bone defect used a circular fixator to reduce the defect. Lastly, the placement of bone segments must be evaluated to maintain the movement of the extremity called simultaneous compression of disruption osteosynthesis.[20]

When BT is compared to other techniques involving bone lengthening, BT has the clinical advantage of low soft tissue impact due to non-extension. The distracting force on the BT comes mainly from the traction of the bone callus and the compression of the docking tissue. Related studies have been carried out in vivo in BT which have experimentally provided a model of mechanical behavior during DO bone callus exclusively.[21] The DO technique requires 5 fundamental principles i.e. (1) corticotomy; (2) interruption period; (3) elongation; (4) external fixation; and (5) active movement of the extremity.[20] All the procedure needs full support from all parties as well as a systematic approach from the surgeon, team, and patient.[20] The section of defects performed depends on the site and excessive lavage. The ideal alignment of the fixation technique at least covers half of the diaphysis. During transport, necrosis of bone due to pressure must be avoided.[20] Many factors should be monitored during transport like pace and rhythm. The BT procedure during the elongation process needs transport to the docking location. While bone with vascularization disturbances needs a longer duration. Every week, an X-Ray needs to perform and the internal fixation to be softened. To build ideal alignment, the forces used must be appropriate to avoid deflection segments. The docking procedure used a transport vector. There is a secondary problem like contractures as a consequence of tibial BT.[20]

Docking is the position where bone segments reach or crossed the defect. This procedure must be done quickly and routinely. Moreover, a scar may develop from resection after several weeks. The fibrous tissue formed a scar in the docking site so it must be removed before the procedure is done.

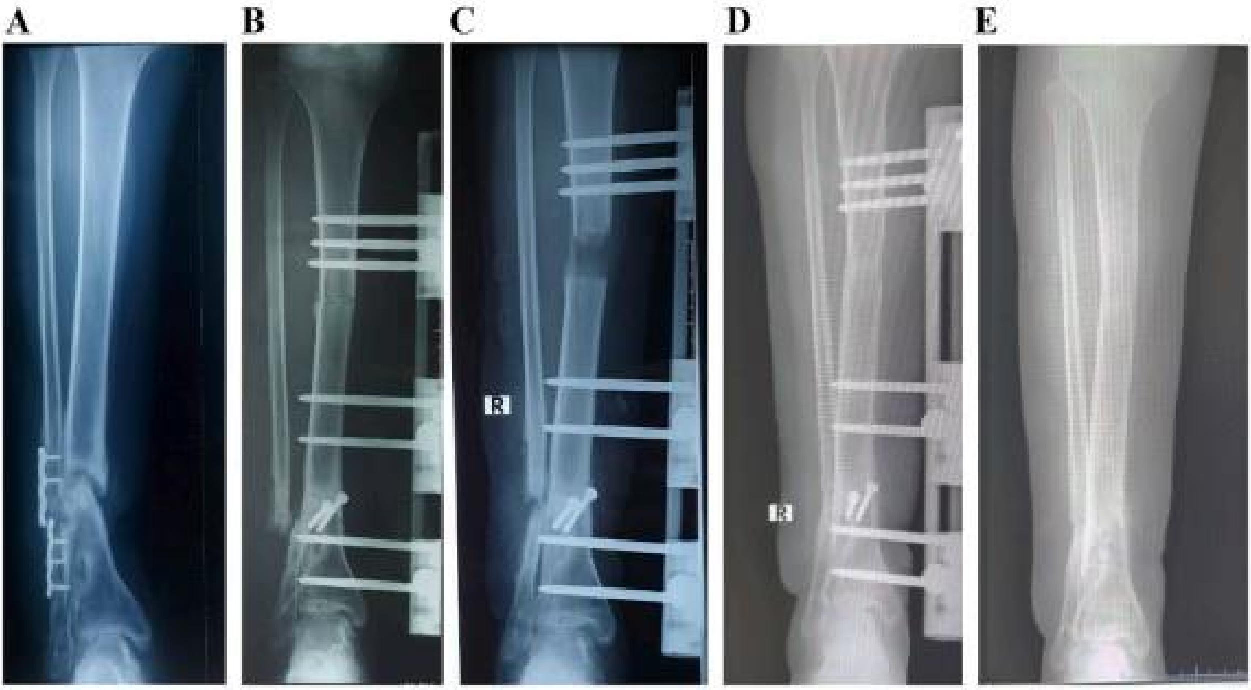

Figure 3. Case of 16 years old, Male, with the diagnosis is infected non-union of the right distal tibia.[22]

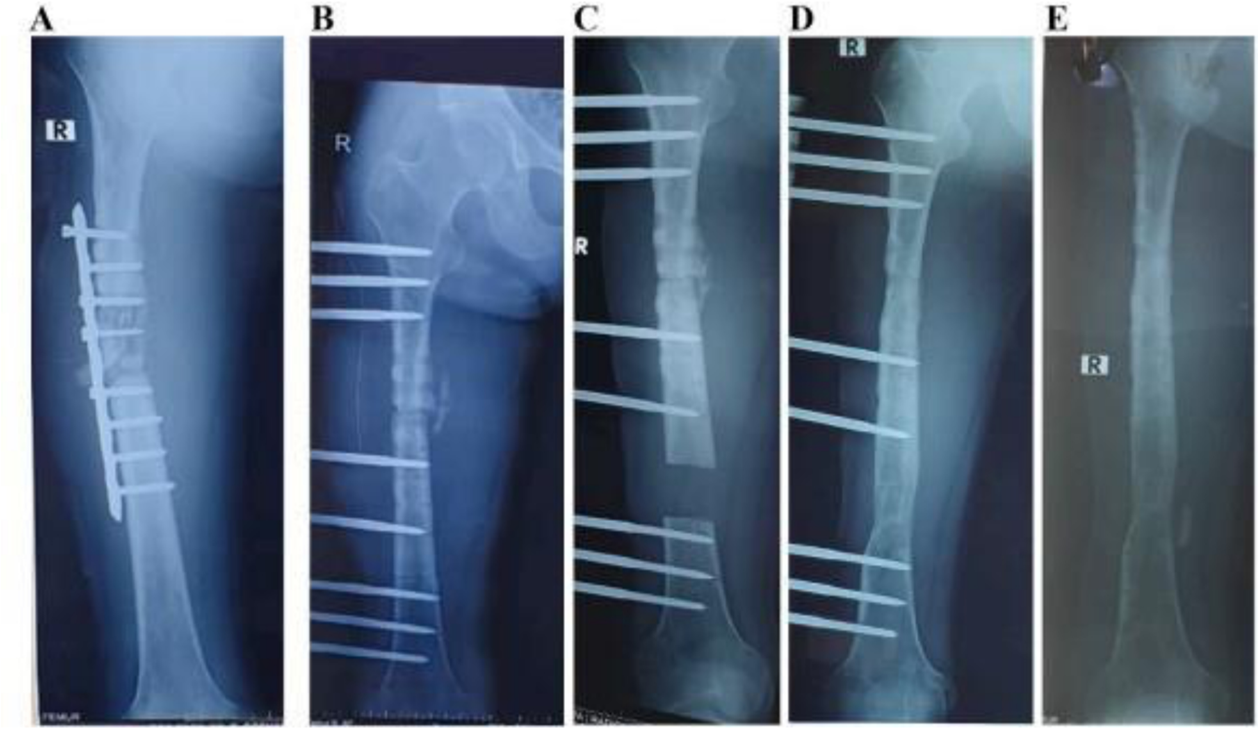

Figure 4. Case of 28 years old, male with infected non-union of right shaft femur after internal fixation with plate and screw.[22]

The surgeon must ensure the best alignment for bone defects, avoid the scar, and regeneration of bone goes well. The healing process requires local and systemic factors such as debridement for promoting rejuvenation.

Bone morphogenic proteins have benefits in dock site healing. After the docking procedure at the maintenance short distance, or after bone contact occurs, the lifting force changes to a compression force at the docking site. Continuous compression periods are individual but regularly consist of 1-2 mm of compression for about 3-4 weeks. The compression degree only showed when adjacent cables are deflected by about 1-2 mm. as the limb length discrepancy persists, limb elongation additionally may happen via the corticotomy site.

Gradual BT can be successful in restoring large-diameter bone, but secondary complications commonly happen cause of the extended period of external fixation. The method showed the use of external fixators shorter using lock plates or intramedullary nails, and the docking place and regeneration area can be internally stabilized, allowing the fixator is releasing earlier during the consolidation period.[20]

After surgery, a person will need to stay in the hospital for 3 to 4 days. While in the hospital, patients with external fixators will be given instructions on how to care for external fixator pins and how to keep them clean. The process of lengthening or interrupting usually begins 7 days after surgery.

The time it takes to fill the gaps depends on the length of the gaps or voids that need to be filled. A general rule of thumb is that it takes one month to form bone for every centimeter (0.4 inches) of length gained. In adults, it can take 3 to 4 times longer. Additional time will be required for the docking site to heal, so it is not uncommon to have to wear an external fixator for 6 – 12 months. Patients with inner nails will elongate at the same rate. Inner nails are usually removed within 1-2 years.

SHORTENING AND RE-LENGTHENING

When an elongation of 4 cm or less is required, acute shortening and lengthening (ASRL) are preferred.[24] The ASRL procedure aims to produce an acute docking to make the bony gap are closing, distract at the corticotomy place, and get the required length. This method has many advantages over bone transport. These

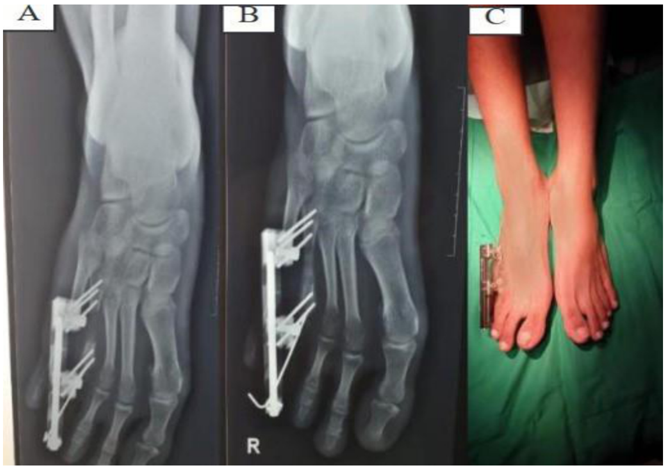

Figure 5. Radiography of bone lengthening for brachimetatarsia.[23]

advantages are a higher rate of the union at the docking place, robust mechanical construction, fewer complications, and easier alignment. One of the difficult problems that often occurs is the bone fusion of the docking site which generally fails in bone transport techniques. Some of the problems that can result in bone misalignment at the docking place are skin folds, soft tissue entrapment, also bone mal-alignment.[18]

During the process of the ASRL, compression between the bony edges directly can be managed and soft tissue entrapment can be avoided. During compression procedures, primary bone grafts may also be performed. Therefore, the docking site unification could be further evaluated by the ASRL technique. As a result of our study recently, necrosis skin around the docking place of the tibia case led to one case of nonunion of the docking site. Along with the shortening procedure, there is a poor skin/soft tissue condition that can lead to skin necrosis and should be highly considered during the ASRL procedure. Another issue to consider during this procedure is the formation of calli at the site of the disturbance.[18]

LIMB LENGTHENING DEVICES

In the last 1 decade, limb-lengthening devices have evolved. The first attempt only used frame traction. Unilateral fixation is the standard method of fixation for long periods. Method options consist of unilateral external or ring fixation (Ilizarov, TSF), intramedullary solid nail as a mechanical or motor-independent technology, or in combination with an external device during the disruption phase (extension over the nail).[25,26]

External Ring Fixation

One of the third can solve multidimensional problems using translation. Ring construction can be done using wire and screw as local control. The updated procedure only needs a small surgery field compared with traditional ones.[2,23,25]

Unilateral External Fixation

This method is best indicated for modest lengthening at short to medium distances. This method applies to all age groups. Although it avoids bulk and multi-pin or -wire fixation of the ring fixator, does not prevent transfixion of the pin muscle, which is a major problem in cases of femoral elongation. The attractive ease of surgical application (percutaneous placement of 4-6 pins, clamping, and rod fitting) contrasts the cantilever design and eccentric loads, which offer less mechanical control than ring construction. Monolateral fixation is usually unable to withstand muscle strength during excessive lengthening. Secondary malalignment, premature cessation of elongation, unilateral premature consolidation, and realignment procedures for angulation >5° under anesthesia are potential sequelae.[12,15,26]

Lengthening Over Nail (LON, Monorail Method)

Different strategies to be applied in the distraction and consolidation phases aim to reduce the total fixator time by placing a solid intramedullary nail at the time of the osteotomy simultaneously with removing the external device at the end of the distraction method.[26] Bost and Larsen in 1956 introduced that LON is technically more demanding than unilateral ring or fixator placement: after reaming, the nail is temporarily placed, then pins and wires under and distal to the outside of the nail, followed by nail extraction, placement of an external fixator, osteotomy and definitive nail insertion.[27] nails are locked after the distraction phase to stabilize the length and axis obtained before removing the fixator. In the earliest case, the nail is not strong enough to stabilize through the consolidation phase but can meet the minimal goal of stable alignment through the distraction phase. Early release of the fixator results in delayed union, fracture, pseudoarthrosis, malalignment, or loss of length.[28,29]

Intramedullary Lengthening Nails

In contrast to the LON, the nail is fully loaded during distraction and needs to withstand both eccentric and cyclic loads during load bearing during the consolidation phase. Full load bearing without crutches is permitted if the radiograph shows new bone formation bridging the

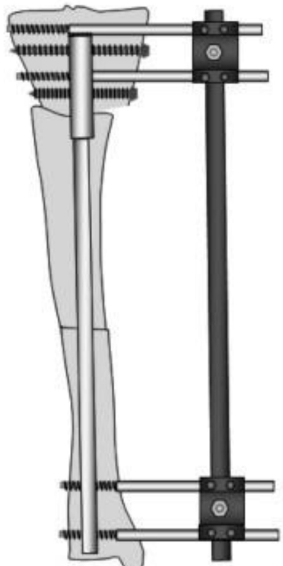

Figure 6. This picture is showing the intramedullary nail locked not distally but proximally to make sliding for lengthening.[30]

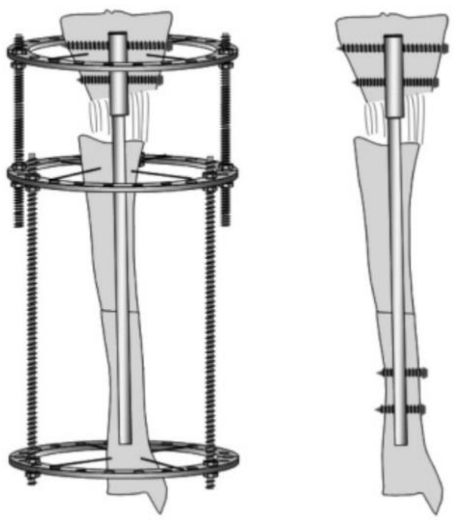

Figure 7. Lengthening Over Nail (LON).[30]

two cortex.[31] Following Ilizarov's fundamental appreciation of the biology of guided three-dimensional regeneration and bone formation, the next milestone was shaped through the development of the widespread intramedullary nail. this is true for more modest deformities after the end of the growth period and requires the size of the medullary canal to match the length of the bone.[26,32]

By the late 1980s, Albizzia had applied mechanical devices clinically, then in the early 1990s, the unique motorized implant, the Fitbone nail appeared. These nails have many potential advantages including less scarring, better body image, psychological well-being, improved aesthetics, no irritation by pins and wires, less frequent infections, less pain, avoiding secondary axial drift, and reduces joint stiffness. , higher activity levels during lengthening consolidation, less risk of neurovascular compromise due to wire or screw insertion, faster rehabilitation, and increased ability to work during and after treatment.[3,33]

Albizzia is a fully implanted nail that is activated by a torque of 20^o along the longitudinal axis of the limb. The Fitbone is an electronic motorized extension spike that does not require rotational motion to extend and has been reported to have 3-17% of device-related reoperation rates.[27,28] These spikes have significantly fewer complications than Albizzia spikes and change physiological forces by at least 3° of rotation during normal gait or manually by up to 9° with less oscillation compared to gait with an attached ratchet mechanism (roller grip) and threaded rods) into an irreversible one-way disturbance. The level of interference is monitored by an external handheld magnet-based sensing device. Both of these devices have been mostly used in Europe and their use increased after the report.[10,26]

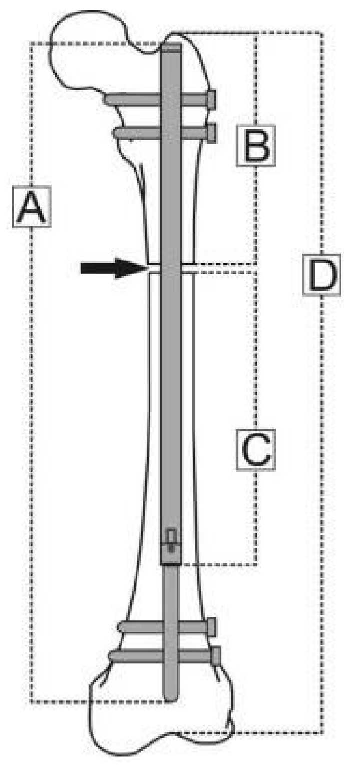

Figure 7. Intramedullary Lengthening Device.[34]

The ISKD (The Intramedullary Skeletal Kinetic Distractor) was the first FDA-approved intramedullary lengthening nail. These nails are activated by a clutch mechanism and are expected to provide comfortable elongation. It bears much fewer complications than Albizzia nails. It converts the physiological force of at least 3° of rotation during a normal gait (or manually up to 9° with less oscillation compared to walking) with the inherent ratchet mechanism (roller grip and threaded rod) into an irreversible one-way disturbance. the severity of the disturbance is monitored by an external handheld magnet-based sensing device. Magnetically actuated telescopic spikes, PRECICE, the second most recent FDA-approved device, are in widespread use worldwide. The advantage of PRECICE is precise control of distraction and reduction of pain during lengthening.[11,35]

COMPLICATION

The outcome of bone elongation is influenced by the clinical experience of the surgeon operating and the length of distraction significantly. there is no difference between tibial or femoral elongation, this is about higher age not congenital or acquired problems, unilateral fixation, severe deformity, and the number of acute corrections which can have several negative impacts additionally. Complications can include wound edges and bone necrosis, osteomyelitis, pin canal injury, and infection, bone nonunion and malunion, joint stiffness, tendon adhesions, and pain. Abbott and Saunders have summarized complications of limb lengthening. There are various classifications of complications, whether simple or complex, greater or lesser, or outcome affection.[3,35]

Pain and pin site infection is the most common complications in patients. Pin site infection is a common orthopedic problem that can show from wires or percutaneous pins. this situation complicates the use of percutaneous fracture pins, skeletal traction pins, and external fixation. techniques to prevent and optimally treat it are still unclear. The pin site is easy to infect because of the disruption of the skin barrier. One series stated that pin site infection was the most general complication of external fixation, with a prevalence of up to one hundred percent in the research group.[13,36] Most pin-site infections can be managed with improved wound care and short-term oral antibiotics. Serious complications such as deep tissue infection and osteomyelitis can occur in up to 4% of cases. Other complications that can occur are Pin loosening, increased pain, use of pain medication, and delayed mobilization. Pin removal may be necessary in severe cases that fail to respond to antibiotic treatment.[14,16]

Due to the combination of factors related to the patient's health and external fixators, not all patients are susceptible to pin site infection. Patient factors associated with a higher risk of pin site infection include intrinsic medical comorbidities and increasing patient age. In addition, medications are taken and immune status can also affect the risk of infections such as diabetes, rheumatoid arthritis and collagen vascular disease, and steroid use.[37,38]

Parameters on the external fixator also affect the risk of pin site infection. In the study cohort of 27 patients, there was an increase in the duration of pin fixation associated with a higher rate of pin site infection for a total of 178 pin site infections. In a previous study, the infection rate was 2.5- fold greater in patients with external fixators who underwent active correction than in those who did not. Although pin site infection is a complication, some serious problems may occur which jeopardize treatment goals and increase patient morbidity. The most severe consequence of superficial infection is Osteomyelitis which can arise from infection of superficial pin sites in up to 4% of cases.[14,17]

Pain is the commonest complaint, occurring mostly during the distraction phase and so decreasing gradually, but often persists throughout the whole distraction and consolidation process. the primary healing response occurs by week 2-3, and is usually amid loss of appetite and depression, triggered by mental stress and of unknown causes. Pain is initially caused by symptoms, stretching of the periosteum, contraction as transfixion of wires or pins, and soft tissue and bone inflammation related to pins and wires. distraction and exercise peak at nighttime. Intense pain may end up in disruption or cessation of elongation and a minimum of impeding joint movement, load bearing, and functional load from regeneration.[37,38]

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