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International recognition of the Ilizarov bone reconstruction techniques: Current practice and research (dedicated to 100th birthday of G. A. Ilizarov)

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Abstract

The Ilizarov method is one of the current methods used in bone reconstruction. It originated in the middle of the past century and comprises a number of bone reconstruction techniques executed with a ring external fixator developed by Ilizarov GA. Its main merits are viable new bone formation through distraction osteogenesis, high union rates and functional use of the limb throughout the course of treatment. The study of the phenomenon of distraction osteogenesis induced by tension stress with the Ilizarov apparatus was the impetus for advancement in bone reconstruction surgery. Since then, the original method has been used along with a number of its modifications developed due to emergence of new fixation devices and techniques of their application such as hexapod external fixators and motorized intramedullary lengthening nails. They gave rise to a relatively new orthopedic subspecialty termed "limb lengthening and reconstruction surgery". Based on a comprehensive literature search, we summarized the recent clinical practice and research in bone reconstruction by the Ilizarov method with a special focus on its modification and recognition by the world orthopedic community. The international influence of the Ilizarov method was reviewed in regard to the origin country of the authors and journal's rating. The Ilizarov method and other techniques based on distraction osteogenesis have been used in many countries and on all populated continents. It proves its international significance and confirms the greatest contribution of Ilizarov GA to bone reconstruction surgery.

Key Words: Ilizarov method; Ilizarov apparatus; Distraction osteogenesis; Bone lengthening; Bone defect; Bone transport; Arthrodesis

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Core Tip: The Ilizarov method of bone reconstruction involves bone repair and new bone formation. It is based on the biological phenomenon of distraction osteogenesis that is used for bone lengthening and deformity correction. The Ilizarov bone transport is a salvage procedure for a number of conditions, including large bone defects and infection. The method gave an impetus to new developments in bone reconstruction surgery based on the regeneration potential of bone tissue. Acceleration of distraction regenerate consolidation is one of the objectives of the current research in new bone formation.

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INTRODUCTION

Reconstructive surgery is performed to recover body parts that are affected aesthetically or functionally in congenital defects, developmental abnormalities or trauma. Bone reconstruction is the procedure of repair, rebuilding, and reshaping of skeleton bones. The goal of bone reconstruction surgery is reparation and creation of vital bone tissue with a variety of treatment methods available. It involves the management of bone injuries and their sequelae such as nonunion, post-traumatic bone defects and bone infection as well as bone deformities and shortening of the extremities due to acquired conditions or congenital malformations. It aims to correct bone loss, length and axis, reshape a limb segment and change its malposition so that to restore or improve its anatomy and functions.

The Ilizarov method is one of the current methods used in bone reconstruction. It originated in the middle of the past century and comprises a number of bone reconstruction techniques performed with a ring external fixator developed by Ilizarov GA (1921-1992) in 1951 in the former Soviet Union[1]. Professor Ilizarov GA (Figure 1) and his team were searching for solutions to develop external fixation (EF) techniques to treat the pathology of long and short bones of both upper and lower limbs, cancellous bones of the skull, pelvis and spine, and joint disorders at one of the largest orthopedic centers for limb reconstruction founded in Kurgan (Russia) in 1971[1-4]. Bone repair and reconstruction with this method are realized by means of applying compression or distraction forces to bone fragments for bone consolidation, axial alignment or new bone formation through the phenomenon of distraction osteogenesis induced by tension stress with the Ilizarov apparatus based on external supports and transosseously drilled wires that, driven with threaded units, are able to produce multiplanar actions on bone fragments. The scientific activity of the Kurgan institute for traumatology and orthopedics promoted basic research on the investigation of bone and soft-tissue regeneration[1-4]. The fundamental and clinical studies on the principles of bone regeneration and reconstruction using the Ilizarov tension-stress effect were disclosed in the author's monograph and several publications that appeared in the English language at the end of the last century[2-4]. They have been considered as major publications of the author and still are his most read works that have been cited more than 1500 times. The Ilizarov bone compression-distraction method, implemented with the author's apparatus, has been called the classical Ilizarov method[1].

The Ilizarov method techniques became known to the world orthopedic community and started to be used in several European countries in the 1980s. Since then, the original method has been used along with a number of its modifications and developments due to emergence of new fixation devices and techniques of their application[1,5,6]. The geography of their application has expanded much while the advancements in bone reconstruction that followed are of international significance and gave rise to a relatively new orthopedic subspecialty which has been termed limb lengthening and reconstruction surgery (LLRS)[7,8]. The purpose of this update was to



Figure 1 Ilizarov GA at the beginning of his career in Kurgan (1960). Photo courtesy of the Ilizarov Center Museum.

summarize the clinical practice and research in bone reconstruction with the Ilizarov and LLRS techniques published in the last 5 years with a special focus on their modification, advance, and recognition by the world orthopedic community.

BONE FIXATION DEVICES

Internal or external bone fixators are mechanical means in bone reconstruction ensuring the stability of a fractured or osteotomized bone, bone compression or distraction, and guided fragment transport. The Ilizarov system that comprises circular external fixator modules and techniques of their application for specific clinical situations[4] has experienced many modifications over the last 50 years[9,10]. Development and progress in bone fixation devices have been greatly influenced by the Ilizarov's "revolutionary entrance" to the world of orthopedics and aimed at constant improvement of clinical outcomes and patients' comfort. External fixators (the Ilizarov apparatus, hybrid and hexapod external fixators, the Orthofix limb reconstruction system, the Taylor Spatial Frame) are the main devices in bone reconstruction surgery that involves new bone formation and correction[5,6,10]. The conventional circular external fixator has been enhanced with innovative configurations, pin and ring modifications, wire and half-pin coatings that can potentially decrease infection rates in thick soft-tissue limb segments while parts fabricated from carbon fibers make the whole circular frame weight lower[5,9]. Monolateral rail external systems have been used for a better comfort of patients undergoing a bone lengthening procedure in the femur[6]. Computerized circular fixators and motorized intramedullary lengthening nails which ensure distraction osteogenesis have been called the major orthopedic advances in the techniques of limb lengthening[5]. However, they are either dependent on specialized computer software and computed tomography (CT) data or costly for the health systems and therefore cannot be used on a large scale. New systems have been designed based on a commercially available motorized lengthening nail for an all-internal segmental bone transport and optional lengthening but their application has been still under investigation[11]. Motorized internal lengthening plates for lengthening in the situations in which intramedullary nailing is contraindicated have been recently under development and might be a major advancement in the field of limb lengthening[12].

Nevertheless, despite the emergence of innovative devices, the Ilizarov-type external fixators remain affordable and preferred devices for management of a great variety of orthopedic conditions due to good clinical results achieved by their application, fast bone tissue formation during callus distraction, much less shear forces compared to unilateral external or hexapod fixators, versatility and lower costs[6]. Moreover, their manufacture has been organized by international and national companies in many countries of the world.

CURRENT CLINICAL PRACTICE AND RESEARCH IN THE ILIZAROV TECHNIQUES OF BONE RECONSTRUCTION

Our review is based on a comprehensive literature search for clinical studies and research on the current use of the Ilizarov techniques for bone reconstruction or their modifications in PubMed, Scopus and Web of Science databases written in the English language and published in the period from 2016 to 2020 with a special emphasis on the international representation of their authors and journals of their publication. The studies available from the journals included into the international indexing systems above mentioned were grouped according to their targeted applications, as described by Ilizarov GA[1,4]. The international influence of the Ilizarov method on the current state of bone reconstruction was reviewed in regard to the origin country of the authors and the impact factor that measures journal's citations, and therefore shows journal's significance for the world orthopedic audience.

Fracture repair

The use of EF in the management of fractures is an old concept. Ilizarov GA and his Kurgan team attempted to design a set of the external apparatus parts that could be assembled into frames for definitive treatment of bone injuries and on any bone segment, including hand and foot bones[4]. However, the evolution of fixation means and of the Ilizarov techniques over the years has specified the fracture types for which the Ilizarov external frames are more efficient. First of all, those are complex open and closed comminuted fractures which are not amenable to open reduction and internal fixation or cast immobilization[13,14]. Indications include pediatric juxta-articular distal radial, distal femoral, distal humeral and distal tibial fractures that are comminuted, complicated, and/or open[15]. The basic principles of the Ilizarov fixation for fracture repair in children avoid additional injury to the growth plate with K-wires, enable careful and accurate reduction without interfragmentary compression, ensure anatomic alignment and fracture stability, preserve periosteal blood supply and allow for joint motion and early weight-bearing. Management of complex pediatric tibial fractures (open injuries, with bone loss or soft-tissue compromise) with the Ilizarov fixator was found safe, effective and reliable with good functional results and health-related quality of life during treatment[16]. Numerous published reports regarding complex trauma reflect the utilization of the Ilizarov techniques in adults, especially for para-articular injuries[17-24]. The Ilizarov bone transport for isolated and *comminuted tibial* fractures with bone defects or tibial deformities was found effective after studying its long-term outcomes and complications at one center for more than 30 years[25]. The Ilizarov ring fixator was recommended as an effective treatment modality for open comminuted distal femur fractures and resulted in high union rate, adequate alignment and satisfactory functional outcomes[17]. It can be reliably used and showed good clinical and quality-of-life results in adult trauma for tibia plateau and pilon fractures[18-22]. Clinical and radiographic outcomes of the Ilizarov technique for high-energy pilon and severe tibial plateau fractures (Schatzker IV-VI) were accompanied by minimal complications or impaired functions. Definitive fixation with circular external fixator in the patients with multiple traumatic injuries was effective in a comparative study evaluating its outcomes *vs* plating for complex Schatzker VI tibial plateau fractures with better union rates, lower infection and compromised soft tissues problems despite some walking impairments detected[18]. There was no difference regarding the rate of deep infection, reoperations, range of knee motion and concerns about physical satisfaction between the two groups treated for proximal tibial fractures with the Ilizarov frame or locking plates[22]. Neglected tibial pilon fractures treated with the Ilizarov frame healed without deep infection and ankle arthrodesis was avoided in most cases[21]. The use of EF for treating displaced intra-articular calcaneal fractures was an alternative to plating and screw fixation with good results achieved by clinicians in most cases due to early mobilization of the peritalar joints and early post-operative loading[23,24]. Long-term functional outcomes of definitive treatment utilizing bone transport for exposed comminuted tibial fractures with bone defects were in line with the literature[25].

The Ilizarov fixator was used in elderly patients for tibia plateau fractures, pilon fractures, ankle fusions, non-unions, deformity correction and miscellaneous trauma [26]. It was concluded that there was no difference between the subgroups of diseases concerning the physical and mental health. First reports on Ilizarov EF for periprosthetic femur and tibial fractures after total knee arthroplasty (TKA) have appeared and have been judged as a feasible and low invasive treatment option providing stable fixation, early post-operative mobilization and no major complications what is

especially important in elderly individuals after TKA[27]. Microvascular fibular grafting was combined with the Ilizarov circular fixation for large acute bone defects in severe trauma with acute bone loss[28]. And finally, placement of the Ilizarov external frame has been much used as a temporary bone fixation means in polytrauma cases and acute compartment syndrome due to high-energy trauma in the lower limbs [29]. The authors of the studies point to the advantages of the Ilizarov fracture stabilization such as maintaining the frame till union, early mobilization, restoration of the normal lower extremity alignment, versatility, and improved union rate in patients with multiple traumatic injuries, including exposed fractures associated with soft tissue trauma.

Long-bone nonunion and defects, including infected ones

The management of bone defects and nonunion continues to be a subject of great interest in the international orthopedic literature[30,31]. A contemporary surgeon has a number of options with proven clinical evidence for management of bone defects and nonunion. Depending on the anatomical location and the size of the defect, current treatment techniques range from acute shortening to vascularized bone grafts, the Ilizarov bone transport and the Masquelet induced membrane technique[31-33]. As shown by several comparative studies, these treatment options have their advantages and limitations. However, the Ilizarov bone transport has been the most frequent practice in nonunion and defect management, especially in infected tibia[34,35]. Current clinical investigations focus on the need for complete eradication of infection through radical debridement[34-39]. Deep femoral infection resulting from intramedullary fixation of closed femoral fractures was resolved with staged treatment that included radical debridement and continuous canal irrigation, followed by monolateral bifocal bone transport[36]. The technique of an L-shaped partial corticotomy with preservation of intact and uninvolved posterior tibial bone was proposed that reduced circular fixator duration in the cases of focal tibial osteomyelitis and bone deficit of 8 cm after debridement[37]. Extensive debridement of all the devitalized tissues and bone transport was a reliable solution in the treatment of gunshot bone defects of the tibia[38]. On the contrary, limited debridement was enough to control infection and achieve good results without radical resection in managing chronic osteomyelitis in pediatric cases[40]. Both bone transport and soft-tissue flaps were used concurrently for management of post-traumatic composite bone and soft tissue defects[41]. EF techniques were found to play a key role in the management of nonunion after Monteggia injuries[42,43]. Lengthening using external fixators was possible in bone resection defects due to tumors[44,45].

Much research has been done in finding solutions for filling critical-sized bone defects in order to promote faster new bone formation utilizing distraction osteogenesis[30,31]. There is a variety of more or less biologic alternatives for the reconstruction of defects, but still distraction osteogenesis undoubtedly has the highest potential for remodeling[31]. One of them is trifocal treatment (two lengthening sites) that shortens EF duration[38]. It was associated with better results compared with bifocal treatment (one lengthening site) for defects of > 8 cm, despite a longer operative time in the trifocal group. Several mechanical solutions utilizing compression and distraction were proposed for failed distraction osteogenesis in large bone defects[46]. One more technique is ipsilateral fibula expansion that is an option of radial instead of longitudinal distraction osteogenesis. Gradual fibular transfer with the Ilizarov external fixator was used in post-traumatic and post-infection large tibial bone defects[47,48]. Although the induced membrane technique has gained much popularity in bone defect treatment, the Ilizarov bone transport remains the main tool in the situations with bone deformity and limb length discrepancy[31]. Its main merits are viable new bone formation to bridge the defect, high union rates and functional use of the limb throughout the course of its many-months treatment, preventing disuse osteoporosis[33-35,49].

Long-bone lengthening and deformity correction

Most modifications of the classical Ilizarov method refer to limb lengthening and deformity correction. First, it was the Taylor Spatial frame supplied with computer guidance for long-bone lengthening and deformity correction[5,6,50]. Then, EF was supplemented by internal fixation with a nail. The combined modifications used currently are lengthening over nail and lengthening and then nailing techniques[6]. One more combined technology is the use of flexible intramedullary HA-coated wires along with the Ilizarov apparatus[51]. These techniques apply external fixators in the lengthening procedure and intramedullary nails in the regenerate consolidation phase to protect the regenerate. However, the comparative studies evaluating the efficacy of

bone formation and prevalence of complications show that they are superior to the conventional method only in regard to the EF index and decrease in the total time of being with the external fixator on[52]. The most recent developments are motorized implantable lengthening nails that provide reasonable lengthening magnitudes[6,53-55]. Despite the complications reported in small series of patients, the new technology of motorized intramedullary nails (MIMN) has simplified upper limb lengthening surgery and made lower limb lengthening more comfortable for patients[53]. Monolateral EF lengthening was compared with MIMN lengthening in children with congenital femoral deficiency and similar lengthening parameters[54]. The MIMN group had lower complication rates and better range of motion at the end of distraction and at consolidation. MIMN technology yields better results for range of motion, which is one of the benefits to patient's quality of life. Improved patient comfort and psychological tolerance, faster recovery of activities, low infection rates and absence of fractures in the regenerated bone are the merits of MIMN against the limitations, such as maximum distraction of 5 cm and the fact that it cannot be used if the growth plates are still open. The PRECICE nail was found to carefully manage the rate of distraction to prevent complications in bone consolidation but the remote controller and the cost were found its weak points[6,55]. Moreover, it was reported that reamed intramedullary nailing showed an adverse effect on bone regeneration during the distraction phase in tibial lengthening[56].

Limb deformity and shortening remains a main issue of bone reconstruction in pediatric orthopedics and its correction is a necessity for a variety of rare congenital conditions[57-61]. EF systems are preferred by the surgeons in pediatric cases[57-59]. Ilizarov two-ring tibial lengthening was found effective in maintaining segmental alignment, efficient in callus production and relatively comfortable for pediatric patients with few significant complications[58]. Monolateral external systems for femoral lengthening were used children and adolescents[59]. Despite the popularity of guided growth systems, the EF role in pediatric deformity correction is significant and can be played by different external devices that allow multiplanar corrections[62]. Nevertheless, Ollier's disease, fibrous dysplasia, osteogenesis imperfecta and other metabolic diseases are still great challenges for orthopedic surgeons[63-66]. Titanium or hydroxyapatite-coated elastic nails in combination with an external fixator may be a way out in limb lengthening and deformity correction of abnormal bone in children [61,65]. These thin HA-coated implants show osteoactive properties and do not migrate as reported by long-term follow-ups. Upon external frame removal after completion of correction, they remain in situ for reinforcement of the abnormal bone in patients with metabolic bone disorders and skeletal dysplasia. Correction through combined bony realignment and lateral collateral ligament tightening in achondroplasia was reported with good or excellent subjective outcomes[66].

Very good results were achieved in humeral lengthening with the Ilizarov techniques. Although the motorized nails were also attempted for this purpose, more magnitude was achieved with EF[67-69]. A series of extensive lengthening in patients with achondroplasia and hypochondroplasia was compared showing complications by bone segment, and between the techniques of simultaneous bilateral lengthening and crossed lengthening[70]. Humeral lengthening in that series was associated with significantly fewer complications and quicker healing than lower-extremity lengthening. The crossed lengthening technique in the lower extremity had a greater incidence of malalignment and leg-length discrepancy compared with the transverse technique. This experience may be useful for limb lengthening done for esthetic purposes[6,71,72]. Recently, limb lengthening for esthetic purposes in patients with constitutional short stature performed either with the Ilizarov-type fixator in the tibia or MIMN in the tibia and femur has become very popular. It was shown to be safe and was judged beneficial to the patients in regard to their social capabilities and self-confidence. Yet, patients should be well informed about the complications and risks of the esthetic lengthening surgery[72].

The basic osteotomy techniques were discussed in regard to bone formation and the study stressed the importance of the procedure for qualitative distraction osteogenesis [73]. The regular 1-mm rate of daily lengthening, confirmed in the historical experiments by the Ilizarov's team[4], should be followed with any fixator or adjusted down if problems appear in order to have stable bone regeneration[48]. The regenerate condition and consolidation is of primary concern to allow full weight-bearing[74]. Current research in limb lengthening has been based on the experiments which are aimed at distraction osteogenesis acceleration and faster regenerate maturation that take many months to complete efficient bone formation. The protocol of injecting bone marrow aspirate concentrate in multiple areas of poor regenerate was used to correct delayed union in achondroplasia during distraction osteogenesis, but the study evokes

concerns of bias in confirming its role for faster healing[75]. Several studies used pharmacological agents to improve regenerate formation. Teriparatide, the bioactive component of parathyroid hormone, was delivered by daily subcutaneous injections after bone-transport docking[76,77]. It was stated that teriparatide treatment during the consolidation phase of distraction osteogenesis doubled the mineralization rate of the regenerate when compared to no treatment. The experiment on a canine model attempted automated high-frequency distraction with a daily 3-mm rate and confirmed that the bone had the potential for regeneration under the conditions described but there were concerns about the response of soft tissues and joints[78]. Histological differences were observed in bone and muscle tissue when Ilizarov fixation was supplemented by intramedullary HA-coated thin nails compared with no intramedullary stabilization in that experiment. Only few recent studies were found on the effect of mechanical forces and some agents to accelerate or improve bone regeneration[76-79]. Thus, the problem still remains on the agenda of future research. There has been an increasing interest in technologically based surgical strategies for limb deformity correction and lengthening[80]. Nevertheless, the recent advances in an increased use of computers and mobile devices along with the application of dynamic hexapod EFs and MIMN are still based on the principles described by Ilizarov GA and Paley D.

Rare conditions

Although there is a lot of investigation on the management of congenital pseudarthrosis of the tibia (CPT) and an extreme interest to the Masquelet technique attempted recently for this rare pathology, the appropriate solutions have not been found yet[81-86]. Latest reports support a combined basis in CPT management for both the biological and mechanical components of the conditions, utilizing the Ilizarov EF and intramedullary rod stabilization along with a corticocancellous bone autograft. It could ensure a statistically significant reduction in the number of refractures compared with standalone fixation methods. A multicenter study of the influencing factors in the management of Crawford-type IV CPT with follow-ups till skeletal maturity showed that the use of the Ilizarov technique, transfixing the ankle and subtalar joints, use of a cortical graft and not operating on the fibula were associated with better outcomes than combining intramedullary nailing with the Ilizarov technique and the use of bone morphogenetic protein[85]. The induced membrane technique combined with the Ilizarov bone transport has been tried to improve the outcomes of CPT management and demonstrated promising results in regard to avoid refractures[86]. It also included morphological investigation of the human induced membrane and its potential for osteogenesis. Injections of bone marrow aspirate concentrate in the pseudarthrosis site after focus removal in combination with circular EF achieved faster bone healing compared with EF only, and the lower refracture rate but a longer follow-up would be required to determine if the results of this adjuvant therapy will hold up over time[87]. It was revealed that additive rhBMP-2 might shorten the time to initial healing of pseudarthroses but not guarantee bony union[81]. Severe cases of proximal tibial dysplasia associated with CPT were treated using lengthening either with a transphyseal distraction or an osteotomy directly next to the physis[88]. It found that lengthening through the physis had a lower healing index (faster healing) than after metaphyseal corticotomy but should be best done near maturity. Reconstruction with several procedures along with EF ended in limb salvage in tibial hemimelia[89,90]. Lengthening and deformity correction with the Ilizarov principles were reported for multiple hereditary exostoses of the forearm, radial deformity, radial clubhand, ulnar longitudinal deficiency[91-94]. A large series of children with hereditary exostoses was reported who were treated by either unilateral or circular EF for lengthening[91]. A technique of bifocal distal radial osteotomy for acute angular correction distally and lengthening with EF more proximally was described for patients with distal radial deformity and concurrent shortening[92].

Foot bone malformation and deformities

The Ilizarov techniques of gradual correction in multicomponent foot deformities and gradual soft tissue distraction with open releases and/or bony procedures can achieve a pain-free and plantigrade foot[95-99]. Placement of the Ilizarov-type frame on the foot and its adjustments require both an experienced surgeon and a motivated patient but the techniques achieve the goals both in bone reconstruction and functionality of the foot. In complex cases, distraction osteogenesis should be reserved as a salvage solution and should be performed at specialized centers. The techniques for foot pathology are implemented with a number of frame modifications, including hexapod external fixators[99]. The techniques may be regarded as salvage procedures in

neglected adult clubfoot, challenging ulcerations, ankle joint arthrodesis for treating Charcot neuroarthropathy despite the complications[96,100-103]. Thus, a hybrid technique of circular EF and an intramedullary nail coated with antibiotic cement salvaged lower limbs in most patients and achieved a functional and clinically stable foot in infected neuropathic ankles[104]. Infected ankles were also salvaged with the Ilizarov method[104-106]. Reconstruction of the hind foot and ankle with concurrent lengthening through a distal tibial corticotomy utilizing the Ilizarov frame was found comparable to other treatment alternatives[107]. Modifications were proposed for rare congenital malformations of the foot, including brachymetatarsia and cleft foot[108-110]. Different foot and ankle frame assemblies were grouped into a few standard hexapod configurations and foot treatment strategies were demonstrated[111].

Hand malformation and deformities

The Ilizarov-type external mini-fixator and some other small external fixators were specially developed for hand bone injuries, lengthening, congenital malformation and deformities[112-115]. They confirm the success of the ideas of Ilizarov GA in utilizing distraction osteogenesis and soft tissue traction in the management of hand pathology [4].

Joint disorders

Ilizarov's ideas also contributed to joint reconstruction surgery[4,116]. Reconstruction techniques continue to find applications in the management of complex pediatric hip pathology. Recently, good results have been reported using EF systems for correction of proximal femoral deformities secondary to slipped capital femoral epiphysis, Perthes' disease in children, coxa vara, sequelae of pediatric hip septic coxitis, and ischemic deformities of the hip[116-121]. A safe and effective technique of a low-profile Ilizarov external fixator was applied for developmental coxa vara following an acute, opened wedge subtrochanteric valgus-flexion-derotation femoral osteotomy using a percutaneous multiple hole drilling for treating multiplanar proximal femoral deformities in children[117]. Proximal femoral and triple pelvic osteotomies and the Ilizarov frame module were successfully used for treatment of adolescent developmental hip dysplasia[119]. Pertrochanteric osteotomy and femoral neck lengthening by distraction were efficient in treatment of proximal hip ischemic deformities in children [120]. Management of a chronic, traumatic posterior hip dislocation in an 8-year-old boy by open reduction, grafting, femoral shortening, and stabilization with articulated iliofemoral EF was described[121].

Joint distraction with EF frames is not a frequent procedure but the published studies report on clinical improvements in adult patients with knee osteoarthritis [122]. Despite the short follow-ups, small sample sizes and high frequency of pin tract infection reported which is of concern, since most patients will further require joint replacement, the technique might allow delaying joint replacement surgery for several years[123]. Ankle arthrodiastasis was also shown as an option for patients with end-stage primary or post-traumatic ankle osteoarthritis[124]. The authors believe that distraction within the joint optimizes the intraarticular environment for equilibration of hydrostatic pressure, promoting subchondral morphoangiogenesis, and decreases subchondral sclerosis, thereby mitigating pain. The process allows for joint salvage as an alternative to arthrodesis or ankle implant arthroplasty. The authors see joint distraction to be a useful approach to the management of ankle pain secondary to loss of functional joint surface.

Unfortunately, arthrodesis is still a salvage surgical procedure for knee and ankle joints in cases of infected total arthroplasty, tumor, failed arthroplasty or posttraumatic complication. Arthrodesis of the knee with the Ilizarov external fixator has been found successful in achieving quality of fusion and recovery of the limb supporting function [125,126]. Effective ankle arthrodesis using either external or internal fixation was reported but better outcomes were achieved in the EF group[127]. The technique of tibiototalcalcaneal arthrodesis in patients with and without diabetes, closed arthrodesis in infected neuropathic ankles and infected ankle fractures with segmental bone-loss using Ilizarov concepts were assessed as salvage procedures[107,128,129]. An interesting study on the use of shoulder arthrodesis for septic arthritis of the shoulder due to proximal humerus osteomyelitis was presented[130].

Other pathology

We should finally mention flat bone reconstruction based on the Ilizarov principles. The apparatus for transpedicular EF in spinal pathology was first experimented on animals under the supervision of Ilizarov GA and later developed by his followers at the Ilizarov Center in Kurgan[131]. It could provide gradual controlled correction for

high-grade kyphoscoliosis in adolescents and transition to internal fixation following its removal with preserved correction at long term. The Ilizarov's experimental team also investigated gradual expansion of skull bones and surrounding soft tissues. It was applied for traumatic skull defects and brain vascularity stimulation after brain stroke but the techniques remained on the stage of uncompleted clinical trials. On the contrary, the role and significance of craniomaxillofacial distraction procedures have been much discussed in the specialized literature and has been found applicable in craniofacial deficiency or dentofacial anomalies that are corrected with distraction procedures and special devices[132,133]. Another Ilizarov's idea of stimulating the vascularity in chronic ischemic diseases in the lower extremities has been revived and its modification has been called tibial transverse distraction[134,135].

THE INTERNATIONAL IMPACT OF THE ILIZAROV METHOD ON THE EVOLUTION OF BONE RECONSTRUCTION SURGERY

The laws of compression-distraction osteogenesis due to tension-stress effect were discovered by Professor Ilizarov GA and his team of scientists more than 60 years ago and the techniques were termed "transosseous osteosynthesis"[1-4]. Our literature review shows that they have been still largely implemented with the external apparatus that bears his name. The versatility of the assemblies constructed from the Ilizarov apparatus set of parts resulted in a great variety of possible applications in bone reconstruction surgery that are fracture repair, bone nonunion, mal-union, bone defects, limb length discrepancy, long-bone deformity, hip disorders, knee arthrodesis, ankle arthrodesis, foot deformities, foot bone lengthening, anomalies and fractures of the hand. It is the main tool in the management of complex intraarticular fractures, bone transport and bone infection in the tibia, foot deformities and ankle arthrodesis. No other system of external bone fixation is able to produce so many options and variants used for bone recovery. The biological phenomenon of distraction osteogenesis developed by Ilizarov GA may be considered one of the greatest achievements in bone reconstruction surgery.

Our goal was to present to your attention the studies on the current international practice and research in bone reconstruction that have been based on the Ilizarov's ideas. The search for literature in the international databases has revealed a huge amount of practical studies that encapsulate a broad spectrum of pathologies treated with interventions or devices developed within the LLRS subspecialty due to the impact of the Ilizarov method. The original Ilizarov techniques of bone reconstruction and their modifications or innovations have been investigated at a variety of institutions across the world but the main centers of clinical research and practice are located in the United States, United Kingdom, China, Russia, Italy, Egypt, and India [136,137]. It is well seen from Table 1 that presents the number of authors per country that published their studies in the period under investigation (data from PubMed platform of the National Library of Medicine, United States) (Table 1).

The impact of the Ilizarov method on bone reconstruction surgery is of great international value. Interestingly, but the shortcomings of the Ilizarov method which are mainly related the ring fixator such as transfixation of muscles and other soft tissues with wires and half-pins, pain, pin-tract infection, and psychosocial limitations imposed on the patient due to prolonged use of the Ilizarov circular fixator have led to vigorous research and development of new devices able to decrease or avoid them. However, the principles of new bone tissue formation discovered by Ilizarov GA have been recognized as universal. Ilizarov-minded surgeons continue to use this method due to its efficacy proven by more than a half-century practice. LLRS has been regarded as an orthopedic subspecialty that emerged due to the advancements in bone reconstruction after the introduction of the Ilizarov method[138]. National limb lengthening and reconstruction societies, though under various names, have been active worldwide. The first one was the Association for the Study and Application of the Ilizarov Methods (ASAMI) that appeared in Italy and was the one that played the major role in the popularization of the Ilizarov techniques. Its activities were broadened by the International ASAMI and the International LLRS which hold biannual meetings around the world. Such meetings and courses were held in Milan, Baltimore, Cairo, Lima, St. Petersburg, Barcelona, Bombay, San Paolo, Miami, Liverpool, Dhaka, Sydney, and other cities. The nearest meeting has been scheduled to be held in Mexico in 2022. There is a LLRS specialty day at the annual meeting of the American Academy of Orthopaedic Surgeons at which bone reconstruction surgeons from around the world present their studies and hold workshops. The *Journal of Bone*

Table 1 Number of authors per country that published their studies on bone reconstruction with the Ilizarov techniques or their modifications (PubMed search results for 2016-2020)

#	Country	Number of authors	%	#	Country	Number of authors	%
1	China	105	19.1	26	Spain	4	0.7
2	Russian Federation	52	9.5	27	Nigeria	4	0.7
3	United States	43	7.8	28	Belgium	3	0.5
4	United Kingdom	40	7.3	29	Canada	3	0.5
5	India	39	7.1	30	Indonesia	3	0.5
6	Egypt	39	7.1	31	Serbia	3	0.5
7	Japan	22	4.0	32	Singapore	3	0.5
8	Poland	21	3.8	33	Cameroon	3	0.5
9	Pakistan	18	3.3	34	Iran	2	0.4
10	Turkey	16	2.9	35	Netherlands	2	0.4
11	Italy	15	2.7	36	Finland	1	0.2
12	Germany	12	2.2	37	Iraq	1	0.2
13	Bangladesh	10	1.8	38	Ireland	1	0.2
14	Switzerland	9	1.6	39	Israel	1	0.2
15	Thailand	8	1.5	40	Kuwait	1	0.2
16	Australia	7	1.3	41	Mexico	1	0.2
17	Greece	7	1.3	42	Morocco	1	0.2
18	Tunisia	7	1.3	43	Philippines	1	0.2
19	France	6	1.1	44	Puerto Rico	1	0.2
20	South Korea	6	1.1	45	Saudi Arabia	1	0.2
21	Austria	5	0.9	46	Sudan	1	0.2
22	Brazil	5	0.9	47	Portugal	1	0.2
23	Denmark	5	0.9	48	Argentina	1	0.2
24	Malaysia	5	0.9	49	Lebanon	1	0.2
25	South Africa	4	0.7		Total of authors	550	100

and *Joint Surgery* of the Association of Bone and Joint Surgeons publishes annual guest editorials on the topic of new studies in limb lengthening and deformity correction [136].

Our survey which is based on the data from the international databases for the latest 5-year period has revealed that more than 150 journals dedicated their space to the topic under our discussion. These journals published more than 750 articles on the Ilizarov techniques of bone reconstruction and their modifications submitted by the authors from 50 countries. SCImago metrics on ratings of the journals in the field of Orthopedics&Sports Medicine based on Scopus® database shows that numerous studies have been published in the journals of high citation level and international value (Table 2). The high-rated journals, popular among orthopedic surgeons, such as *Injury, Bone and Joint Journal, Journal of Paediatric Orthopaedics, International Orthopaedics, Journal of Foot and Ankle Surgery* have published the biggest number of the articles (Table 2). Table 2 also lists the countries of the authors that published their clinical and basic research on the Ilizarov techniques, their modifications and related fields of study. The most read and cited orthopedic journals also appear to have a wide authors' representation from around the world.

Authors from the countries with large population such as China, the United States, India and Russia came first in the line. China was formally introduced with the Ilizarov method in 1990 but has become the leader in the last 10 years. The interest to the original method evoked new ideas and applications, including continuous basic research on the biological mechanisms of distraction osteogenesis and its translation to

Table 2 Publication of studies on the Ilizarov techniques or their modifications in the international journals of high scientific impact and specialized limb lengthening and reconstruction surgery journals in 2016-2020 (SCImago metrics and Scopus database)

#	Journal title	Society, institution or publishing company	SJR 2019	Number of articles	Origin country of the authors of the studies
Quartile Q1					
1	<i>Injury</i>	British Trauma Society, Australasian Trauma Society, Saudi Orthopaedic Association in Trauma	0.904	40	Australia, Austria, China, Egypt, Germany, India, Italy, Japan, Malaysia, Poland, French Republic, Serbia, South Africa, Spain, Switzerland, Turkey, United Kingdom, United States
2	<i>Bone and Joint Journal</i>	British Editorial Society of Bone and Joint Surgery, United Kingdom	2.375	14	Australia, Austria, China, Egypt, Germany, India, Italy, Kuwait, Pakistan, Russia, South Korea, Switzerland, United Kingdom
3	<i>International Orthopaedics</i>	International Society of Orthopaedic Surgery and Traumatology (SICOT)	1.533	14	Austria, China, Egypt, Ireland, Japan, Russia
4	<i>Journal of Orthopaedic Trauma</i>	Orthopaedic Trauma Association, AO Trauma North America, Belgian Orthopaedic Trauma Association, etc.	1.023	9	Egypt, Japan, Switzerland, United Kingdom, United States
5	<i>Archives of Orthopaedic and Trauma Surgery</i>	Springer Verlag, Germany	1.152	8	Belgium, Egypt, Italy, Netherlands, Poland, Russia, Serbia, South Africa, Switzerland, United Kingdom
6	<i>Journal of Pediatric Orthopaedics</i>	Pediatric Orthopaedic Society of North America (POSNA)	1.19	7	Egypt, India, Iran, Republic of Korea, United Kingdom, United States
7	<i>Clinical Orthopaedics and Related Research</i>	Association of Bone and Joint Surgeons	1.487	5	Australia, China, United Kingdom
8	<i>Knee</i>	British Association for Surgery of the Knee, the Australian Knee Society, and the German Knee Society	1.083	4	China, Greece, Italy, Turkey
9	<i>Scientific reports</i>	Universities and research institutions, United Kingdom	1.341	4	China, Poland
10	<i>HSS Journal</i>	Hospital for Special Surgery, United States	0.76	3	Israel, Italy, Russia, United States
11	<i>Orthopaedics and Traumatology: Surgery and Research</i>	French Society for Orthopaedic Surgery and Traumatology (SoFCOT)	0.949	3	Egypt, France, United Kingdom
Quartile Q2					
12	<i>Journal of Orthopaedic Translation</i>	Chinese Speaking Orthopaedic Society (CSOS) and the International Chinese Musculoskeletal Research Society (ICMRS)	0.73	16	China, Hong Kong, United Kingdom
13	<i>BMC Musculoskeletal Disorders</i>	BioMedCentral, part of Springer Nature	0.76	12	China, Japan, Mexico, Poland
14	<i>Journal of Pediatric Orthopaedics Part B</i>	International Federation of Paediatric Orthopaedic Societies (IFPOS)	0.411	12	China, Egypt, India, Poland, French Republic, Spain, United Kingdom, United States
15	<i>Journal of Foot and Ankle Surgery</i>	American College of Foot and Ankle Surgeons	0.619	11	China, Egypt, Greece, Japan, French Republic, United Kingdom, United States
16	<i>Medicine (United States)</i>	Medicine®, universities and research institutions in the United States	0.639	8	China, Japan, Poland, United States
17	<i>Journal of Orthopaedic Surgery and Research</i>	BioMedCentral, part of Springer Nature	0.669	7	China, Denmark, Germany, Poland, United Kingdom, United States
18	<i>Journal of Orthopaedic Science</i>	Japanese Orthopaedic Association	0.56	6	China, Japan, South Korea, United Kingdom
19	<i>Journal of Children's Orthopaedics</i>	European Paediatric Orthopaedic Society (EPOS)	0.597	5	Egypt, France, Italy, Russia, Switzerland
20	<i>Acta Orthopaedica et Traumatologica Turcica</i>	Turk Ortopedi ve Travmatoloji Derneği	0.442	4	China, Russia, Turkey
21	<i>European Journal of Orthopaedic Surgery and Traumatology</i>	Springer-Verlag France SAS, part of Springer Nature	0.681	4	Egypt, Greece, Italy, Serbia, United Kingdom, United States
22	<i>Orthopaedic Surgery</i>	Chinese Orthopaedic Association and John Wiley and Sons Australia, Ltd.	0.618	4	China, Thailand

23	<i>World Journal of Orthopaedics</i>	Baishideng Publishing Group	0.798	4	Egypt, Russia
24	<i>Foot and Ankle Surgery</i>	European Foot and Ankle Society	0.716	3	China, Egypt
Quartile Q3					
25	¹ <i>Strategies in Trauma and Limb Reconstruction</i>	British Limb Reconstruction Society	0.481	30	Australia, Denmark, Egypt, India, Italy, Pakistan, Russia, Singapore, Turkey, United Kingdom, United States
26	<i>Indian Journal of Orthopaedics</i>	Indian Orthopaedic Association (IOA)	0.39	10	Greece, India, Italy, Russia
27	<i>Journal of Clinical Orthopaedics and Trauma</i>	Delhi Orthopaedic Association	0.469	10	India, Italy, Russia, Thailand
28	<i>Journal of Orthopaedics</i>	Prof. PK Surendran Memorial Educational Foundation and Indo Korean Orthopaedic Foundation	0.2	10	China, India, Indonesia, Japan, Russia, Turkey, United Kingdom, United States
29	<i>Ortopedia Traumatologia Rehabilitacja</i>	Foundation of Medical Education, Poland	0.195	6	India, Italy, Poland
30	<i>Revista Brasileira de Ortopedia</i>	Brazilian Society of Orthopedics and Traumatology	0.437	6	Brazil, China, India, Russia
31	<i>Chinese Journal of Traumatology</i>	Daping Hospital and the Research Institute of Surgery of the Third Military Medical University	0.385	5	Brazil, India, Russia, Singapore
32	<i>Clinics in Podiatric Medicine and Surgery</i>	Clinics series, ELSEVIER	0.326	5	United States
33	<i>Acta Orthopaedica Belgica</i>	The Belgian Orthopaedic Trauma Association	0.31	4	Egypt, India, Russia, United States
34	<i>Malaysian Orthopaedic Journal</i>	Malaysian Orthopaedic Association and ASEAN Orthopaedic Association	0.25	4	India, Pakistan
Quartile Q4					
35	¹ <i>Genij Ortopedii</i>	Association of Study and Application of Methods of Ilizarov (Russia)	0.151	109	Bangladesh, France, India, Russia, Switzerland, United States, Uzbekistan
36	<i>Trauma Case Reports</i>	Affiliated to <i>Injury</i> Journal	0.15	4	Japan
37	<i>Mymensingh Medical Journal</i>	Bangladesh Academy of Sciences	0.159	3	Bangladesh
38	² <i>Journal of Limb Lengthening and Reconstruction</i>	Association of Study and Application of Methods of Ilizarov and the International Limb Lengthening and Reconstruction Society	-	80	India, United States, United Kingdom, Portugal, Brazil, Japan, Egypt, Canada, South Africa, Saudi Arabia, Malaysia, Russia, Italy, Germany, Lebanon, Greece, Israel, Argentina, Australia

¹Specialized limb lengthening and reconstruction surgery (LLRS) journals.

²Specialized LLRS journals not included in Scopus. SJR: Scientific Journal Ranking (SCImago Journal and Country Rank).

the clinical practice^[137]. One of the newest editions is the *Journal of Orthopaedic Translation* of the Chinese Speaking Orthopaedic Society (CSOS) and the International Chinese Musculoskeletal Research Society (ICMRS) which main goal is to publish papers that “identify and fill scientific knowledge gaps at the junction of basic research and clinical application (from bench to bedside) or community application (from bench to community)”. It published 16 articles on the application of the techniques based on the Ilizarov method and basic research in a special issue (November 2020), titled *Ilizarov Techniques in China for 30 years: From Research to Clinical Translation* that focuses on shortening of treatment duration by stimulating distraction histogenesis ^[135,137].

There are three specialized journals that are meant by their founders to be dedicated to LLRS. *Strategies in Trauma and Limb Reconstruction* of the British Limb Reconstruction Society has been adopted as the English language journal on this subspecialty by several ASAMI and LLRS societies (Brazil, Egypt, Japan, LLRS North America, LLRS South Africa, LLRS Nordic, ASAMI Philippines, Pakistan, Malaysia, South Korea, CEFM China)^[1,66,73]. *Journal of Limb Lengthening & Reconstruction*, the official publication for the International ASAMI and ILLRS, is a platform for exchanging the opinions on the topics of bone and joint reconstruction that has issued six volumes since its initiation but unfortunately still lacks indexing by the interna-

tional databases of Scopus, Web of Science and the PubMed platform[8,74]. The *Genius of Orthopaedics (Genij Ortopedii)* issued at the Ilizarov National Medical Research Center for Traumatology and Orthopedics (former Russian Ilizarov Scientific Center for Restorative Traumatology and Orthopedics) by ASAMI Russia has been included in the Scopus database and provides a free on-line access to its volumes both in Russian and English[86]. These journals show the evolution and the main tendencies in LLSR in the post-Ilizarov era reflected in clinical and basic research.

It is no doubt that the use of the Ilizarov method has been discussed in general medical and orthopedic journals that are issued in national languages or are read at national level. Those journals may not be included into the famous databases and are not so much known to the international orthopedic community but could testify on the geography of the Ilizarov method distribution across the continents[139]. The studies written by the authors from Cameroon and Nigeria on Ilizarov limb reconstruction in Africa conclude that the use of the Ilizarov method has been sparsely reported on the continent but should be “popularized in the countries with limited resources because it would be an attractive alternative to the amputations that are sometimes performed” [140,141].

Although the Ilizarov method requires a lot of training and expertise to perform it successfully, a great number of surgeons throughout the world have mastered its principles and basic techniques to improve or save their patients’ lives. The three databases that we have reviewed include the studies of the authors practicing in 50 developed and developing nations from all the populated continents. We have undertaken a lot of effort to fulfill the noble goal of this investigation but acknowledge that our data are far from complete but they prove that the Ilizarov’s ideas of bone reconstruction have been shared in clinical practice and followed across the world.

CONCLUSION

The Ilizarov's principles of bone reconstruction have stood the test of time and have been internationally recognized. It has been confirmed by numerous studies published in honored international and national journals. The Ilizarov method and other techniques based on distraction osteogenesis have been used in a great number of countries and all continents. These facts prove its international significance and confirm the greatest contribution of Ilizarov GA to bone reconstruction surgery. Undoubtedly, the great heritage he has left to the world should be emphasized once again in 2021, the year when his 100th birthday is marked.

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