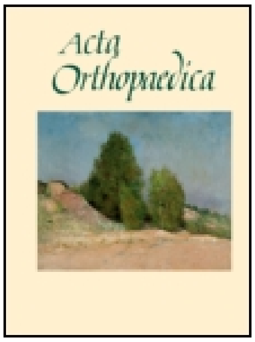

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Reconstructive surgery of the human tibia by use of external ring fixator and the Ilizarov method

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This work is dedicated to the Biomechanics Laboratory

Department of Orthopaedics

Rikshospitalet, University of Oslo, Norway

and to the Head of the Laboratory

Dr. Harald Steen, MD/Ph.D

Contents

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Acknowledgements

The clinical work with patients comprising the current thesis started back in 1992 at Sophies Minde Orthopaedic Hospital. Thanks to Thor Heyerdahl (1914–2002), who brought together a multinational crew on his trips with RA 1, RA 2 and Tigris, the Ilizarov method was introduced to the Western world. Later, professor John Herzenberg from the USA was invited to our hospital to teach us the mystery of this method. My former chief and teacher, professor Ingjald Bjerkreim, gave me the opportunity to work together with Dr. Erik Rosenlund using the Ilizarov external fixators on bone lengthening and deformity correction. Then the spirit of the present work was made. I am very grateful to both Ingjald and Erik, who believed in my skills as an orthopaedic surgeon and taught me paediatric orthopaedics. They gave me the opportunity to develop the Ilizarov method at Sophies Minde at a very early stage of my career.

I will also like to thank professors Paul Lereim and Terje Terjesen and Drs Roger Sørensen, Johan Emil (Milen) Lange, Gunnar Follerås and Cato Hellum who all contributed to widen my orthopaedic horizon and supported me in the clinical work with deformity cases. Dr. Kjell Bye expanded my use of circular fixators to also include correction of deformities in the upper extremities. Professor Olav Reikerås introduced me to the world of science and invited me to be co-author on various scientific papers. Without his enthusiasm and efficiency I may not have been able to start this work.

Lately, I have been engaged as a consultant at the Orthopaedic department, Rikshospitalet. My present leader, Dr. Trine Sand Kaastad, has made it possible to combine my interest for clinical work at a private institution with clinical and scientific work at her department. Being present only 2 days a week would have been very difficult without help from my very talented colleague, Dr. Joachim Horn, who has been working together with me in the clinics with deformity cases the last few years. He has contributed to develop the use of Ilizarov's method especially with the introduction of the Taylor Spatial Frame. Joachim has been very active in teaching our work both to other colleagues and orthopaedic departments in Norway, and also in presenting papers and abstracts at national and international congresses.

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My patients, I thank you all for your patience and support during the period of treatment. I know that pain and discomfort are side effects of the Ilizarov treatment, but nevertheless, I hope you are happy with the final result.

June, 2008 Leif Pål

Abbreviations

CORA – Center Of Rotation of Angulation
CPT – Congenital Pseudarthrosis of the Tibia
DO – Distraction Osteogenesis
IEF – Ilizarov External Fixator
IFM – InterFragmentary Motion
IM – IntraMedullary
LI – Lengthening Index
LLD – Leg / Limb Length Discrepancy
LLI – Leg / Limb Length Inequality
LON – Lengthening Over Nail
MAD – Mechanical Axis Deviation
ROM – Range Of Motion
RSA – Radio Stereo(photogram)metric Analysis
TSF – Taylor Spatial Frame

Key words

Anisomelia (LLI / LLD)
Bifocal osteotomy
Callotasis (callus taxis = callus distraction)
Congenital Pseudarthrosis of the Tibia (CPT)
Complications
Deformity
Distraction Osteogenesis (DO)
Ilizarov (method / External Fixator, IEF)
IntraMedullary nail (IM nail)
Leg / Limb Length Discrepancy (LLD)
Leg / Limb Length Inequality (LLI, MeSH; Medical Subject Heading)
Leg / Limb lengthening
Lengthening Index (LI)
Lengthening Over Nail (LON)
Malalignment
Malunion
Monofocal osteotomy
Nonunion
Radio Stereometric Analysis (RSA)
Tibia
Taylor Spatial Frame (TSF)

Papers

The present thesis is based on the following papers:

1. Kristiansen LP, Steen H.
   Reduced lengthening index by use of bifocal osteotomy in the tibia. Comparison of monofocal and bifocal procedures with the Ilizarov external fixator
   Acta Orthop Scand 2002; 73(1): 93-97.

2. Kristiansen LP, Steen H, Reikerås O.
   No difference in tibial lengthening index by use of Taylor Spatial Frame or Ilizarov External Fixator
   Acta Orthop 2006; 77(5): 772-777.

3. Kristiansen LP, Steen H.
   Lengthening of the tibia over an intramedullary nail, using the Ilizarov external fixator. Major complications and slow consolidation in 9 lengthenings
   Acta Orthop Scand 1999; 70(3): 271-274.

4. Steen H, Kristiansen LP, Finnanger AM, Kärrholm J, Reikerås O.
   Deformation across the zone of callotasis during loading. Radiostereometric analysis in a patient with achondroplasia
   J Orthop Res 2001; 19(2): 265-268.

5. Kristiansen LP, Steen H, Terjesen T.
   Residual challenges after healing of congenital pseudarthrosis in the tibia
   Clin Orthop 2003; (414): 228-237.

Synopsis

Paper 1

In 49 patients 63 tibial segments were lengthened with the use of one osteotomy (monofocal = 31) or two osteotomies (bifocal = 32) in the same segment. In both groups the Ilizarov External Fixator (IEF) was applied. The Lengthening Index (LI = months in the frame per cm lengthening) was lower in the bifocal group, LI = 1.0 (0.7–2.1) months/cm, in lengthenings with an average of 7.4 (4.9–10.0) cm compared with LI = 1.7 (0.9–4.4) months/cm in monofocal lengthenings with an average lengthening of 4.8 (2.4–7.1) cm. The difference was significant with respect to all the patients operated and borderline significant (p = 0.07) between the patients with overlapping lengthening distances (4.9–7.1 cm). More major complications requiring surgery (16 versus 10) occurred in the bifocal osteotomy group compared to monofocal lengthenings.

Paper 2

We lengthened 20 tibial segments monofocally with the Taylor Spatial Frame (TSF) and compared the results with 27 tibial segments lengthened monofocally with the IEF. Even if the devices have different mechanical characteristics, the results in LI did not differ significantly when compared in the overlapping zone of lengthening distances. The average LI values were found to be 2.4 months/cm in the TSF group and 1.8 months/cm in the IEF group of comparable lengthening distances between 2.4 and 6.0 cm (p = 0.17). The complication rate was similar in both groups with respect to both minor and major complications.

Paper 3

Nine tibial segments were lengthened over nail (LON) using the IEF. The median lengthening was 7.0 (5.5–7.3) cm and the median time with external fixator mounted was 99 (63–125) days. The median LI was 4.4 (2.4–6.1) months/cm. The number of major complications (n = 7) was high with one deep intramedullary (IM) infection needing extraction of the IM nail during the distraction phase, 3 fatigue fractures of the IM nail or interlocking screws needing revision combined with bone grafting, one revision of IM nail only, one removal of interlocking screw and one soft tissue release of the ankle joint. Our recommandation was not to use LON in the tibia.

Thesis at a glance

Paper	Patients N	Segments N	Osteotomies N	Lengthening Index (months/cm) median/average (range)
1	49	63	95	1.4[a] (0.7–4.4)
2	47	47	47	2.7[a] (0.8–8.4)
3	5	9	9	4.4 (2.4–6.1)
4	1	1	2	4.1
5	7	7	7	1.7 (0.8–2.7)
Sum/average	109	127	160	2.2[a] (0.7–8.4)

[a] Average

Paper 4

In a case study we used high-resolution radiostereo(photogram)metric analysis (RSA) to assess global longitudinal compressive deformation (axial strain) across the lengthening (callotasis) zone during loading. An achondroplastic patient undergoing bifocal tibial lengthening with the use of IEF was tested under a load of 71% of the body weight resulting in an axial deformation of 7.7 mm measured across the proximal callotasis zone of 51 mm length; corresponding to an overall linear strain of 15.1%. From this case study we could not draw any general conclusions regarding strain values and healing of the lengthening zone, but in future studies the method may contribute to a better understanding of the role of axial strain in distraction osteogenesis (DO) to create optimal conditions for stimulation of bone formation.

Paper 5

Seven patients aged 2.6 to 7.8 years with congenital pseudarthrosis of the tibia (CPT) were operated on by use of the Ilizarov bone transport method and IEF. All patients achieved healing of the pseudarthrosis during the primary Ilizarov procedure, however, two of the patients needed additional bone grafting. Within a follow-up period of 6–8 years all patients had recurrency of deformities. Five refractures were observed, 4 healed with a new Ilizarov bone transport procedure, while 1 developed a chronic nonunion. All patients had persisting axial deformities with mechanical axis deviation (MAD) of 10 mm or more compared to the contralateral side. Three patients had leg length inequality (LLI) of 20 mm or more. After successful healing in CPT, post treatment axial deformity must be expected.

Introduction

Congenital or acquired limb length discrepancy (LLD) or inequality (LLI), also named 'anisomelia', is a well known condition in any orthopedic practice. Even if LLD is most frequently used, LLI is the official Medical Subject Heading (MeSH) term applied by the National Institute of Health (NIH) in their Medline database. Hence, LLI will be preferably used in the current work. Leg (instead of limb) length inequality is another expression often used synonymously with LLI. The leg could be limited to the lower part of the lower limb between the knee joint and the ankle joint (tibia and fibula), but it is hard to be consistent in the use of these terms. Even if the focus of the present thesis is the tibia, limb and leg will be used interchangeably as identical terms.

Ideally, the word 'segment' represents a complete bone structure, e.g the tibia. However, when a bone is osteotomized, the resulting 2 or more fragments can also be referred to as 'segments', which have occurred in the papers comprising this thesis. The only exceptions from the above nomenclature which are generally accepted, are the terms 'transport segment' used with the Ilizarov method (Catagni 1998) and 'reference and corresponding segments' used with the Taylor Spatial Frame (TSF) (Taylor 2002).

LLI less than 1.0 cm is observed among about 70% of the population (Friend and Widmann 2008) and is usually not associated with symptoms and therefore not treated. Conservative treatment with shoe adjustment is recommended in LLI of 1.0–2.0 cm, and operative treatment with shortening or lengthening procedures should be considered above this level (Steen et al. 1997).

The first limb lengthening procedure was published in 1905 by Codivilla who also pointed out the problem of the soft tissues in lengthenings. He used a plaster cast with a calcaneus pin and periodical lengthenings to prevent soft tissue problems. After this first experience in lengthening of long tubular bones the results were unpredictable and disappointing for a long period of time (Abbott and Saunders 1939, Allan 1951). A comprehensive historical review is given in the thesis of Fjeld and Steen (1989) and in the paper by Wiedemann (1996). Lengthening as the method of choice was not accepted until Ilizarov developed the callus distraction procedure (callotasis) by use of his external ring fixator in the early 1950's in the USSR (Ilizarov 1992, Ilizarov and Deviatov 1969).

Acquired or congenital deformities in the lower extremity may lead to secondary degenerative disease in the concomitant joints (Tetsworth and Paley 1994). Restoration of normal anatomy with respect to both length and axes is therefore of great importance to the patient and the orthopaedic surgeon. Deformities in the proximal femur is of less importance because the spherical hip joint allows a high degree of deformity without a corresponding change in axial malalignment expressed by the global mechanical axis deviation (MAD). Malalignment refers to the loss of colinearity of the hip, knee, and ankle in the frontal plane (Paley 2002). In the distal tibia there is a limited possibility for correction of deformity by the range of motion in the ankle joint and subtalar joints. The hinged knee joint has no capability to correct for deformities in the frontal plane. In addition, the knee joint is located almost in the middle between the two ends of the lower extremity and small deformities located close to this joint will lead to a global malalignment, which needs to be corrected. Hence, in the current work where the tibial segment is in focus, reconstruction of deformities in the tibia both proximally and distally is of great importance.

Discrepancy in limb length is an axial deformity and is often combined with angular deformities. Many methods have been published and described to solve the deformity problem (Aaron and Eilert 1996, Baumgart et al. 2005, De Bastiani et al. 1986b, Hasler 2000, Phemister 1933). Traditionally, orthotic supplement of the required length to achieve equality is the easiest way to help out the patients. However, for practical, cosmetical and functional reasons, there is a limit in the magnitude of shoe lift or use of a lengthening orthosis.

Various surgical procedures may be applied for the reconstruction of deformities where LLI is included solely or as part of a more complex deformity.

Shortening procedures

Physiodesis

Physiodesis is often referred to as epiphysiodesis in the literature. However, with respect to the anatomy the correct term should be physiodesis. The method most often includes permanent closing of the physis by destruction of the growth plate in a growing skeleton distally on the femur, proximally or distally on the tibia, or a combination of these (Bowen and Johnson 1984, Phemister 1933). The procedure may also be used as a temporary closure of the growth plate by use of staples or plates (Blount and Clarke 1949, Buller et al. 2008).

In some cases physiodesis can be applied to correct angular deformities by closing only one side of the physis (hemi-physiodesis) temporarily or permanently (Buller et al. 2008, Khoury et al. 2007). However, physiodesis is an inaccurate procedure which includes a number of uncertainty factors in the correct timing of the surgery. This uncertainty is associated with the various methods being used for assessment of biological maturity by skeletal age (Anderson et al. 1963, Dimeglio et al. 2005, Greulich and Pyle S.I. 1950, Tanner and Whitehouse 1975), calculation of remaining growth (Anderson et al. 1963, Little et al. 1996, Menelaus 1966, Moseley 1978, Paley et al. 2000, Sanders et al. 2007), and the unpredictability of the possible effect of changed microcirculation in the remaining intact growth plates of the involved limb due to transient hyperemia after skeletal trauma (Kellerova et al. 1970).

Physiodesis is usually applied only to reduce the LLI in cases with relatively small differences of 2.0–5.0 cm (Friend and Widmann 2008). It is important to inform the child and parents that the projected standing height will be reduced and the result is not accurate and may only incompletely correct the LLI, and that the child needs the remaining growth period to achieve the final result. In a few cases even overcorrection may occur which can require adjustment with a heel rise or a secondary reconstructive procedure (Little et al. 1996).

Shortening osteotomy

Both the femur and tibia can be used in shortening osteotomy procedures (Kenwright and Albinana 1991), preferentially in skeletally mature patients. However, due to the relatively short contractile elements of the tendon-muscle units in the tibia, only an LLI of 3.0 cm at the maximum should be corrected on this segment to prevent postoperative chronic weakness (Hasler 2000). LLI of this amount is more easily corrected with a shoe lift. On the contrary, in correction of the femur, 10–15% of the original length of the bone may be shortened without permanent weakness of the thigh muscle (Holm et al. 1994, Nordsletten et al. 1994). Many patients seem to be happy with the results after a shortening procedure (Holm et al. 1994), but they have to be informed about the fact that in hypoplasia, a bilateral shortening deformity is created by involving the contralateral, normal leg. Ideally, shortening methods should therefore be used in cases where the malalignment or deformity is diagnosed on the longer extremity.

Lengthening procedures

In most conditions with LLI the pathology is located in the short limb. Hence, lengthening of the involved short limb is more natural and logic than shortening of the normal limb to gain equal limb length. Various procedures have been described to lengthen the tubular long bones with simultaneous correction of angulation and translation.

Physeal distraction

Physeal distraction is often referred to as epiphyseal distraction in the literature. However, with respect to the anatomy the correct term should be physeal distraction. By application of pins on both sides of the growth plate connected with an external distraction device, physiolysis (Monticelli and Spinelli 1981) and gradual lengthening without physiolysis, chondrodiatasis (De Bastiani et al. 1986b) with new bone formation can be achieved. According to Hähnel (1977), this method was introduced by Ilizarov already in 1954. Today, most orthopaedic centers have abandoned these methods due to disturbance of remaining growth in the distracted physis (Bjerkreim 1989, de Pablos and Canadell 1990, Fjeld and Steen 1990). Even if Zarzycki et al. (2002) did not observe any premature growth cartilage fusions after physeal distraction in 40 patients, reduced growth potential could not be excluded.

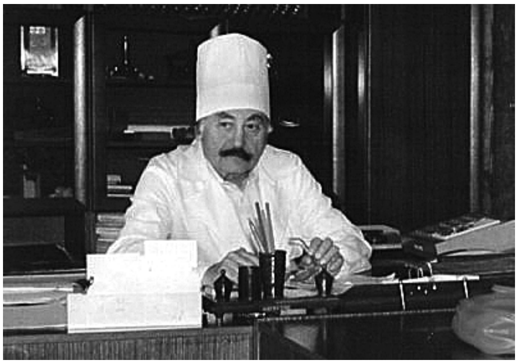
Lengthening osteotomy

Since Codivilla (1905) as the first author described his technique, various method eras with osteotomy followed by acute or gradual lengthening, fixation by external or internal devices and with or without bone grafting has been reported (Birch and Samchukov 2004, Moseley 1991, Wiedemann 1996).

After having been known in Kurgan in Russia for 20–30 years the callus distraction or 'callotasis' technique by use of a ring fixator was first introduced to the orthopaedic surgeons in the Western hemisphere during the 1980'ies, starting in Italy and later expanding to the United States (Catagni 1998). The method has been called "the Ilizarov technique", named after Gavril Abromovich Ilizarov, the Russian orthopedic surgeon who developed the technique in the early 1950'ies in Kurgan, a city located in Siberia east of the Ural mountains in the Asian part of Russia.

From Ilizarov's daughter, Svetlana Ilizarov, who is an MD, working in New York, USA, we have by e-mail (personal communication, August 28, 2006) received helpful extensive information in addition to data we have collected from the literature and from the internet:

Ilizarov was born on June 15th, 1921, in the town Belovezh, in Caucasus in the former Soviet Union, now Belarus. His family consisted of poor peasants of Jewish origin. As a young child he worked with grazing cattle for local peasants to help the family earn their living. He began his education at the age of 11 and became interested in medicine after he was "miraculously cured" from food poisoning by a local doctor. He attended a medical precourse at Dragestanmor and then entered the Crimean Medical Institute in Sinferopel at the beginning of the World War II. He completed his medical education at this institute in 1944 despite the ongoing war. After graduation, he was posed in Dolgovka in the Kurgan region of Siberia, where he worked



GAVRIL ABROMOVICH ILIZAROV 1921–1992 (with permission from daughter Svetlana Ilizarov April 17, 2008)

as a general practitioner. In 1946 he organized a workshop for the development of medical instruments to treat war-injured invalids who returned from the war frontline. At this workshop, he started working with the earliest prototype of his famous circular external fixator. Later, on June 9th, 1952, he patented his fixator, which today is known as the Ilizarov External Fixator (IEF). Through the 1950s and 1960s he widened the indication of the fixator's use to include treatment of LLI, malunion and nonunion.

In 1952, the Krasny Kurgan newspaper reported the treatment of a 12.3 cm LLI with a lengthening procedure by use of his newly developed equipment. He told the newspaper that the idea of using a circular frame came to him after observing a horse cart with its wheels imaging the axle being the fractured bone, and the wheel with its spokes the external frame. Furthermore, the stable, but manouverable construction connecting the horse to the carriage gave him the idea of rods and hinges. He carried out experiments on broken sticks passing wires through the stick fragments and fixing them to rings connected with threaded rods.

Ilizarov became the Chief of the Department of Trauma and Orthopaedics in the Veteran's hospital in Kurgan in 1955. At this time he began basic scientific research on bone healing using his apparatus, and in 1968 his scientific thesis 'Compression osteosynthesis with the author's apparatus' was evaluated worth of the degree of doctor of medical sciences (Shevtsov (Ed) 2008). Ilizarov was not acknowledged in the USSR by the authorities until the successful treatment in 1968 of the famous Soviet high jumper Valery Brumel. However, the nonunion and shortening of the tibia of the famous athletic was treated with the Ilizarov method, and the amazing result of this very difficult condition made the Ilizarov technique well known around in the Soviet Union.

In 1969 the Ilizarov laboratory was affiliated with the Leningrad Scientific Research Institute for Traumatology and Orthopedics. Next year, November 1970, the first symposium on compression-distraction osteosynthesis was held. The USSR Ministry of Health decided to reorganize the Kurgan Regional department subsidiary into an independent scientific institution, named the Russian Ilizarov Scientific Center for Restorative Traumatology and Orthopaedics (RISC RTO). This clinic was built to include a 350-large-animal vivarium and was equipped with the most modern means for basic science research and clinical treatment. Hence, the authorities built the world's largest orthopaedic hospital in Kurgan, and Ilizarov was included in the Society of Orthopaedic surgeons in the USSR.

Ilizarov wrote texts and manuals on his technique which became well known and widely used in the Soviet and it's bloc countries, but yet remained unknown to Western orthopedists. According to Stuart A. Green "It is a testament to how the Iron Curtain controlled information. They were doing Ilizarov procedures in Cuba in the 1970s and no one in the West had ever heard about it; only 90 miles off the shore of Florida and nobody knew" (Beadling 2002).

In November 1980 the Italian alpinist and adventurer, Carlo Mauri, was successfully operated in Kurgan with the Ilizarov method for an infected tibial nonunion with shortening. Mauri had during the 1960's and 1970's been unsuccessfully treated with numerous operations of a tibial fracture after a climbing accident at the mountain Mont Blanc. He developed an infected nounion which after as many as 18 years of unsuccessful treatment persisted chronic and (nontreated) without any further intervention. In 1969, Carlo Mauri, was introduced to Thor Heyerdahl, the famous Norwegian adventurer and archeologist, before his trips with the papyrus boats Ra 1, Ra 2 and Tigris. He was taken on as a part of the multinational crew on the recommendation of an Italian photographer who himself was not able to participate.

From Thor Heyerdahl we have by personal communication (letter from Güímar, Tenerife, Islas Canarias, Spain, dated Nov 9th, 2001) received supplemental information. Heyerdahl tells that he first did not discover that Carlo was injured because of the fact that everyone had a small limping gait due to the uneven surface of the papyrus boat. They were all walking around on the boat barefoot and the shortening was therefore not easy to discover. They were not suspicious even if they discovered that Carlo Mauri used shoes with a couple of cm thicker sole compared to the contra lateral side. However, on the second trip, with the Ra 2, Heyerdahl discovered that Carlo regularly and in secret was treated by the Russian doctor Yuri Senkevich with cleaning of a purulent fistula on his previously injured tibia. After asking, Heyerdahl was explained that the wound had to be kept open to avoid infection of the bone marrow. Yuri Senkevich was the doctor on both the Ra 1 and Ra 2 expeditions and after the trip with Tigris in 1979 he invited Carlo to Russia to see professor Ilizarov in Kurgan to be treated for his infected nonunion and shortening deformity. Carlo Mauri and Ilizarov became good friends during the stay in Russia, and Ilizarov later visited Carlo in Lecco in Italy where he lived together with his family. Thor Heyerdahl was very surprised by the results of the treatment and the explanation how the nonunion was cured. "Yuri knew a miracle doctor in Russia who had developed an instrument which could be applied to the bone to distract the broken parts from each other very slowly. With the use of this technique the bone could be lengthened and the nonunion could simultaneously heal. No one believed in my story and I would neither have, if I did not know Carlo and also was invited to his home in Lecco to meet this miracle doctor". This was actually the introduction to the Italian orthopaedic society and opened up for further invitation to professor Ilizarov to tell about his experiences and teach orthopaedic surgeons all over the world how to use his apparatus. Ilizarov made his first western presentation in Italy in 1981, and the Italian mass media gave enthusiastic opinions about Ilizarov's visit under striking headlines: "The second revolution in Russia" and "Michelangelo of Orthopaedics". A decision to set up an Association on the Study and Application of the Method of Ilizarov (ASAMI) was made up there

(Beadling 2002). In April 1982 an Italian group of orthopedic surgeons including G Monticelli, R Spinelli, A Bianchi-Maiocchi, A Villa, GB Benedetti, M Catagni and R Cattaneo visited Kurgan to learn more about the Ilizarov method. In 1991 the ASAMI group published a text book 'Operative Principles of Ilizarov' edited by A Bianchi-Maiocchi and J Aronson.

Personally, my first experience with the ring fixator and the Ilizarov method was in 1991 when I was a resident at Sophies Minde Orthopaedic Hospital and was introduced to the Distraction Osteogenesis (DO) by professor Ingjald Bjerkreim, chief surgeon of the hospital, dr. Erik Rosenlund and dr. Harald Steen, head of the hospital's Biomechanics Laboratory. As a young orthopaedic resident, I was very lucky to meet professor John Herzenberg on his trip to Norway during a visit in our hospital, when he was introducing the Ilizarov ring fixator, originally designed by Ilizarov. Professor Bjerkreim asked me to participate in the group dealing with deformity corrections by use of the Ilizarov method, and later I became the leader of this activity in our hospital. Trips to Baltimore to see professors Dror Paley and John Herzenberg, visiting Kurgan to see the Ilizarov Institute and its current leader professor Shevtsov, and finally to see the Lecco Institute and professors Maurizio Catagni and Roberto Cattaneo, made me enthusiastic to spend time and work with all the possibilities this method offers.

During the period from 1992 to this date we have operated on patients with various diagnoses and applied the ring fixator for DO on most of the long tubular bones including tibia, fibula, femur, humerus, radius and ulna, and also metatarsals and os calcaneus. In our institution more than 500 circular frames have been applied on patients operated on by myself and collegues for bone lengthening and axial and angular corrections, bone transport, fractures, joint distractions (arthrodiatasis), foot corrections, joint contractures, and arthrodesis. The first lengthening procedures started at the Sophies Minde Orthopaedic Hospital by professor Ingjald Bjerkreim back in 1977 by use of the Wagner method (Wagner 1971, Wagner 1978) with mid-diaphyseal osteotomy made by an oscillating saw, the Wagner unilateral square-shaped external frame with four or six 6 mm diameter Schanz screws and 1.5 mm daily distraction (Bjerkreim and Hellum 1983). At the end of distraction the lengthening zone was suspended by a specially designed internal plate and bone grafting.

During the early 1980'ies the physeal distraction method, although originally described in Russian by Ilizarov (1969), was first known in the Western hemisphere literature by a publication from Monticelli & Spinelli (1981) who on a few patients used an application of a Hoffmann-Vidal bilateral external frame configuration with two 4 mm diameter transfixation pins with central thread on each side of the physis and 1 mm diurnal distraction rate. However, it turned out both from experimental and clinical results that the growth plate lost potential for further growth after this procedure, and use of the method had to be limited to premature individuals close to the end of the growth period (Bjerkreim 1989, Fjeld and Steen 1990). Use of the callotasis method by corticotomy and osteoclasis in the metaphysis, followed by a latency period and DO by 0.75–1.0 mm daily distraction, started in the late 1980'ies, and first with the Orthofix unilateral external frame (De Bastiani et al. 1987). Extended use of the callotasis method with gradual deformity correction by application of an external frame system with ring configuration and hinges started in the early 1990'ies (Ilizarov 1992). In the late 1990'ies the lengthening over nail method as described by Paley et al. (1997) was applied in our hospital with callotasis lengthening by use of the IEF for distraction over an intramedullary nail. Callotasis with an IM telescopic nail and internal distraction was also performed in a few patients by manual external rotation of the leg (Guichet et al. 2003). Callotasis lengthening with multiplanar, gradual correction of deformities along 6 axes by the hexapod TSF with 6 oblique struts between 2 rings started out in 2002 (Taylor 2008).

The purpose of the current study is to present our results of reconstructive lengthening of the tibia with focus on the treatment time expressed by the lengthening index and complications, with comparison of different methods, surgical techniques, diagnoses and biomechanical properties. One experimental study is included where we wanted to explore the micromovement across the callotasis zone associated with loading in terms of weight bearing. It is well known that the volume and quality of the newly formed bone regenerate differs from patient to patient who is equipped with similar, but various frame constructions and demonstrate a great variation in weight bearing. By this approach we may be able to find an answer to the important question of what is the optimal stimulus for bone formation and healing of the regenerate in limb lengthening.

Aims of study

The present thesis is focused on reconstructive surgery of the human tibia by use of external ring fixators and the Ilizarov method. The aims of the current work are:

1) to compare monofocal versus bifocal lengthening osteotomy by use of the Ilizarov External Fixator (IEF) with emphasis on healing evaluated by Lengthening Index (LI) and complications;

2) to compare two different types of external ring fixators (Taylor Spatial Frame versus IEF) used in limb lengthening and reconstructive surgery with respect to difference in mechanical properties, healing evaluated by LI and complications;

3) to assess our results by use of the combination of internal fixation and IEF in lengthening of the tibia over an intramedullary nail by evaluation of healing of the newly formed bone and related complications;

4) to explore deformation across the zone of callotasis during weight bearing in limb lengthening by use of the IEF and assessment by the radiostereometric analysis method;

5) to evaluate our results after treatment of congenital pseudarthrosis of the tibia by use of the Ilizarov bone transport method and IEF during the growth period with focus on post treatment axial malalignment and primary healing.

Summary of Papers

Patients, Methods and Results

Paper 1

We looked retrospectively at 49 patients who underwent 63 lengthenings of the tibia by use of the Ilizarov External Fixator (IEF). Both monofocal (one osteotomy) and bifocal (two osteotomies) techniques were used to perform lengthenings in the tibia with or without simultaneous angular correction. The indications for lengthening and deformity corrections were congenital shortening of one or two legs, acquired shortening after fracture or infection, and major constitutional shortening with the need of bilateral leg lengthening procedures. Most of the patients were adolescents or young adults.

The tibiae were divided into two groups with respect to numbers of osteotomies, with 31 segments (monofocal) and 32 segments (bifocal) in each group, respectively.

The monofocal frames were constructed with 3 rings and 7 wires (3 on the metaphyseal side of the osteotomy and 2 wires on each of the other rings). The tibia was cut in the metaphysis (28 proximally and 3 distally) according to the apex of the deformity.

The bifocal lengthening procedure was performed with simultaneous lengthening both proximally and distally. The bifocal frames consisted of 3 rings, each fixed to the bone with 3 wires. Both groups had the same mid-diaphyseal level of fibular osteotomy, with transfixation to the tibia in both ends to prevent migration of the lateral malleolous or fibular head. The wires were tensioned to 110 kiloponds (1079 N), and both Gigli saw osteotomy (proximal metaphysis) and corticotomy (distal metaphysis) were used. All patients started distraction at day 7 postoperatively with a rate of 1 mm (1/4 mm × 4) daily when monofocal technique was used, and a rate of 1.75 mm (1/4 mm × 4 proximally; 1/4 mm × 3 distally) when bifocal osteotomy was performed. Preoperatively intravenous antibiotics were administered prophylactically, and additional oral antibiotics were given if superficial pin track infection occurred during the distraction and consolidation phases. Complications were recorded and described as major when surgery was required, and minor when peroral antibiotics due to deep pintract infection was administered, joint contracture developed with the need of physiotherapy, transient nerve palsy occurred resulting in change of the distraction rate, or premature consolidation was diagnosed. The frames were removed when symmetric callus or at least 3 cortical sides were observed on biplanar radiographs. The Lengthening Index (LI) was calculated and registered as months in the frame per cm lengthening. Differences in LI values were evaluated and compared by analysis of variance (ANOVA) with a level of $p < 0.05$ being statistically significant. We used a multiphase best fit model (SAS Institute Inc) for graphical illustration. The curve for the monofocal group was best fitted by a quadratic-linear function and the curve for the bifocal group by linear-linear function. To have the same type of function for both groups, quadratic-linear function was applied.

The results in comparing monofocal versus bifocal tibial lengthenings showed that minor complications occurred frequently in both groups. More than one (1.2) minor complications were observed in each operated segment, but there was no significant difference between the two groups. Major complications requiring hospitalisation or surgical intervention, however, were more frequent in the bifocal group. In addition, distal distraction was terminated earlier in all bifocal lengthening cases due to pain and / or contractures. This was not registered as a major complication because the patients did not need hospitalisation. Based on the magnitude of lengthening, the LI was evaluated by dividing the material into three subgroups (small, medium and long). Smaller lengthenings, less than 49 mm, with only monofocal procedures involved, showed a rather high LI. Statistically this group differed from the longer lengthenings both with respect to monofocal and bifocal procedures. Long lengthenings involved only bifocal lengthening osteotomies with more than 71 mm of distraction and had the lowest LI, but did not differ significantly from the medium lengthenings (49–71 mm). In medium lengthening segments both monofocal and bifocal osteotomies were involved and could be compared with overlapping lengthening distances. LI was lower among the bifocal lengthening osteotomies, but statistically significant only in lengthenings of 6 cm or more.

Paper 2

We reviewed 20 tibial deformities with various congenital and aquired ethiologies in 20 patients operated on with monofocal tibial osteotomy and application of the computer-assisted Taylor Spatial Frame (TSF). The results from these patients were compared with the results of 27 monofocal tibial osteotomies operated on by use of the IEF. The indication for using the TSF was shortening combined with multiplanar deformities including axial rotation.

In both groups all osteotomies were performed in the metaphyseal area, 16 proximal and 4 distal in the TSF group and 24 proximal and 3 distal in the IEF group, respectively. In the TSF group all deformity parameters were put into the Internet-based software program (Taylor 2008) and the frames were pre-constructed with the deformity (chronic mode). We used 2 TSF rings with outposts or 2 TSF rings with an additional Ilizarov ring. Each fragment was fixed with 2 wires and 2 or 3 halfpins.

The IEF frames were constructed with 3 rings and mounted to the bone with 7 wires, 3 wires in the bone fragment with a single ring and 2 wires on each of the 2 other rings.

In both groups the fibula was osteotomized in the middle third by the use of an oscillating saw, and fibula transfixation wires were used both proximally and distally to prevent migration of the fibular head or the lateral malleolous. To osteotomize the tibia, we used Gigli saw proximally and corticotomy with the use of multiple cortical drill holes and a curved chisel distally. The distraction started with a rate of 0.75–1.0 mm pr day at day 7 postoperatively in all segments. Preoperatively i.v antibiotics were administered prophylactically, and additionally oral antibiotics were given if superficial pin track infection occurred during the distraction and consolidation phases. Complications were recorded and registered as major if the patients needed hospitalisation or operative treatment to solve the problems, all others as minor. The external devices were removed when symmetric callus or at least 3 cortical sides were observed on biplanar radiographs and the LI was calculated. The statistics were evaluated by use of ANOVA and with adjustment for age by analysis of covariance (ANCOVA; SAS Institute Inc). A p-value < 0.05 was considered statistically significant. For graphical illustration a quadratic-linear function was found as best-fit model by using the software from SAS Institute Inc.

The results regarding overall numbers of complications when comparing segments operated on with the TSF with the IEF, did not differ from each other. However, slow healing or pseudarthrosis was more frequent in the group with TSF. Joint contracture requiring surgery and deep pin track infection were observed in a higher number in patients operated with IEF. The LI decreased significantly from 5.3 months/cm in short lengthenings to 1.3 months/cm in long lengthenings. LI was compared in the zone of overlapping lengthening distances of 24 mm to 60 mm,. Even if the age of the patients in each fixator group undergoing the two different treatments was statistically different, this significant difference was not present among the subgroup of individuals with overlapping lengthening distances. We found no difference in LI between the two groups in this comparable window.

Paper 3

To reduce the time in external fixator we used the Lengthening Over Nail (LON) technique in 9 tibial segments in 5 patients. All patients were operated with lengthening because of constitutional shortness. The median age was 17 (16–21) years and 4 of the 5 patients were females.

In all segments we used an intramedullary (IM) nail with a diameter of 8 mm and IEF with 2 rings and 3 rods. After reaming of the medullary cavity up to 9.5 mm, the IM nail was inserted and the frame mounted with three 1.8 mm diameter wires on each ring. Thereafter the IM nail was removed before a proximal metaphyseal osteotomy was performed by use of a Gigli saw. The fibula was cut in the diaphyseal area with an oscillating saw. The nail was reinserted and locked proximally. The distraction was started 14 days postoperatively with a rate of 1.0 mm (4 × 0.25 mm) per day. After end of distraction the frame was left for another 2 weeks and then the nail was locked distally and the IEF removed. The patients were given oral antibiotics prophylactically during the period of external fixation and full weight bearing was allowed 14 days after distal locking. Complications were observed and additional surgeries registered. The LI was calculated based on the point of time when 3 cortices were observed in biplanar radiographs.

In 9 tibial segments lengthened over an IM nail the median lengthening was 70 mm which represented a relative gain in length of 21%. The median LI was calculated to be 4.4 (2.4–6.1) months/cm, even if the frame was removed at an early stage of 99 (63–125) days. Many complications occurred, the most serious one resulting in a deep IM infection. This patient had the nail removed and the lengthening was stopped immediately at 55 mm of distraction. Only 3 segments in 2 of 5 patients did not require additional surgery. In 5 more segments in 3 patients the nail or screws had to be removed or replaced because of breakage or local irritation of the soft tissue. Three of these segments needed additional autologous bone grafting because of slow healing. One patient had to be treated with Achilles tendon lengthening and posterior capsulotomy 8 months after removal of the fixator due to a persistent joint contracture.

Paper 4

A patient with achondroplasia and standing height of 126 cm was operated bilaterally with bifocal tibial lengthening osteotomies. We used the IEF on both legs. Proximally lengthening with a rate of 1.0 mm per day was performed, while distally lengthening of 0.75 mm daily distraction was used combined with simultaneous axial correction of varus deformity.

The Ilizarov frame was constructed with 3 carbon rings and each ring was connected to another with 3 distraction rods. Each ring was mounted to the bone with 3 wires (diameter 1.8 mm) and the wires were tensioned to 110 kiloponds (1.079 N). Fibula was cut in the diaphyseal area and transfixed proximally and distally to the tibia with wires to prevent migration of the fibular head and lateral malleollus. The last leg operated on had 8 spherical tantalum beads (diameter 0.8 mm) inserted on both sides of the proximal osteotomy as skeletal markers (4 in each fragment). Approval was obtained from the Hospital's Review Board and the patient gave informed consent. Proximally the lengthening underwent automatic distraction with 1 mm per day with an increment of 1/1440 mm every minute, while distally lengthening correction was performed manually (0.25 mm × 3). Six weeks after end of distraction, radiostereometric analysis (RSA) was performed both with and without weight bearing. The amount of weight bearing was registered on a scale to measure the external load on the leg. Two x-ray tubes were angled 40 degrees to each other in the horizontal plane to obtain different projections and the leg was exposed simultaneously by both tubes. The lower leg of the patient was put in the crossing point of the two centered beams, and a calibration cage fitted with embedded tantalum reference markers was mounted behind the patient and anteriorly to the x-ray film cassettes. Both the patient's bone markers and the cassette markers were numbered accordingly to a special code system and put into a computer for a reconstructional procedure. The proximal fragment was defined as a rigid body and the axial movement of the distal fragment under weight bearing conditions was defined. The radiographic examination of global strain across the lengthened bone regenerate was performed with a callotasis zone of 51 mm and with a load of 44 kg (71% of body weight). The calculation was performed as a 'point motion' analysis with 3 tantalum beads in the proximal fragment (defining a rigid body reference) and 2 beads in the distal fragment defining moving points. Hence, 3 of the tantalum beads implanted at the surgery could not contribute to the examination (2 loose and 1 not visualized at all examinations).

The deformation across the lengthening zone during weight bearing in this case study was found to be 7.7 mm under load. The maximum error was estimated to be 0.6 mm. The overall linear strain across the callotasis zone was calculated to be 15% with respect to the above mentioned values.

Paper 5

Seven children (3 girls, 4 boys) with the diagnosis congenital pseudarthroses of the tibia (CPT) were treated with the Ilizarov bone transport method. The median age at operation was 3.2 (2.2–7.8) years. All patients were diagnosed with neurofibromatosis (von Recklinghausen's disease) in addition to the pseudarthrosis. With exception of one boy fibular hypoplasia, fibular pseudarthrosis or both were observed. All patients had 1–3 previous unsuccessfully surgeries performed on the affected leg.

We used 2 different methods of the Ilizarov bone transport. In 5 patients resection of the pseudarthrotic bone, acute shortening and proximal metaphyseal lengthening was used. Indication for acute shortening was distal bone resection of 3 cm or less. In 2 patients with more than 3 cm resection acute shortening was combined with traditional bone transport. A 3 ring IEF was constructed and each ring was fixed to bone with 1.5 mm diameter wires under 90 kiloponds (883 N) tension. Fibula was fixed both distally and proximally to prevent migration, and the bone was osteotomized in the diaphyseal area. After resection of the pseudarthrotic bone, acute axial correction of the distal fragment and foot was performed by use of a retrograde IM wire (diameter 1.8 mm). In one patient the retrograde wire was inserted through the medial malleollus and in the others through the calcaneus for temporary, intraoperative stabilisation of the bone fragments. In all cases a transverse incision was performed to allow skin closure after acute shortening of bone and soft tissue. The tibiae were osteotomized in the proximal metaphysis by use of a Gigli saw to perform bone transport and lengthening. After a latency of 7 days lengthening was started with a rate of 1.0 mm per day (0.25 mm × 4) until the planned required leg length had been restored. In the 2 patients with combined acute shortening and bone transport the IM wire was left during the transport period and in one of these cases also left in situ after frame removal for further protection. Full weight bearing was allowed during the lengthening and consolidation phases and the external device was removed after healing of both the docking and lengthening zones. A plaster cast was put on for 6 weeks and replaced by an orthosis which is standard treatment for the rest of the growth period. Complications were registered, and the patients were followed-up for clinical and radiographical examinations with long standing x-rays at regular intervals. The alignment and orientation with measurements of angular values were assessed and compared with corresponding parameters on the contralateral normal leg. In 1 patient, who had a previous vascularized fibula graft hosted from the contralateral leg, comparisons with the other leg could not be performed because of donor site morbidity with axial malalignment.

Children with CPT achieved healing of the pseudarthrotic site in 5 out of 7 cases without additional surgery using the Ilizarov bone transport method. In 2 patients autologous bone grafting from the iliac crest to the docking area was necessary. The median LI was 1.7 months per cm of lengthening and the median lengthened distance was 54 (26–75) mm. During treatment and post treatment follow-up complications and recurrent deformity occurred in all patients. Four patients had 5 refractures both in the healed pseudarthrosis (2 patients), in the lengthening zone (2 patients) and through a pin hole (1 patient). One patient had a contracture of the ankle joint requiring Achilles tendon lengthening. The same patient had to remove and replace 2 wires due to loosening and pain. One patient had an ipsilateral femoral fracture caused by adequate trauma, and this patient was treated with transarticular extension of the IEF to involve and stabilize also the femoral fracture. Four minor complications occurred as temporary flexion contractures of the knee joint. They were all treated with a dynamic orthosis and physiotherapy. Two patients complained about pain from the affected leg, and reduced running ability was reported by 2 additional patients. However, all but 1 patient participated in regular physical education activities in school. Axial malalignment and reduced range of motion (ROM) of the ankle joint was observed in all patients at the last follow-up 87 (73–94) months post-operatively. There was no difference in ROM in the knees. LLI of 20–48 mm was seen in 5 patients, but only 3 required operative treatment.

Discussion of Papers

Patients

Number

Papers 1 and 2 constitute clinical materials with a significant number of patients (n = 96; 49 and 47, respectively), segments (n = 110; 63 and 47, respectively) and osteotomies (n = 142; 95 and 47, respectively), while Papers 3 and 5 represent a small number of patients (n = 12; 5 and 7, respectively) and segments / osteotomies (n = 16; 9 and 7, respectively). Paper 4 is a single case report. This sums up to a total of 109 patients, 127 segments and 160 osteotomies. However, in Paper 2, 27 patients using the Ilizarov External Fixator (IEF) were selected from the patients presented in Paper 1 to be compared with the Taylor Spatial Frame (TSF) patients. The one achondroplastic patient in Paper 4 was also included in Paper 1 with the opposite leg. Hence, the net sum of patients, segments and osteotomies is 81, 100 and 133, respectively.

Age and Gender

- In Paper 1 the 49 patients were 31 females and 18 males with an average age of 16 (4–48) years.
- In Paper 2 the 20 patients with TSF were 9 females and 11 males with a mean age of 31 (7–59) years. The other 27 patients were recruited from among the 49 patients in Paper 1 and were 16 females and 11 males with an average age of 17 (4–48) years.
- In Paper 3 the 5 patients were 4 females and 1 male with a median age of 17 (16–21) years.
- In Paper 4 the 1 patient was a female 26 years old.
- In Paper 5 the 7 patients were 3 females and 4 males with a median age of 3.2 (2.6–7.8) years.

In practice the use of Ilizarov's method in the current thesis covers almost the whole life span except for the extremes, i.e from a minimum of 2.6 to a maximum of 59 years, which illustrates the method's versatility. Congenital disorders are dominating in frequency among the younger operated patients, while aquired deformities are more frequent in the elderly patients. In Paper 1 there was a wide spread and no significant difference in age of the patients with monofocal versus bifocal osteotomies, while in Paper 2 the age was significantly higher in the TSF group compared with the IEF group which was adjusted for in the analysis. The reason for this difference in age may be the increased number of fracture sequelae compared to congenital disorders with the need of multiaxial lengthening corrections which is a major indication for application of the TSF.

With respect to gender all papers with exception of Paper 1 consist of males and females in fairly equal proportions. The total female/male distribution of 64/45 in 109 patients (or 47/34 in 81 patients) indicates a ratio of about 3/2 which demonstrates an overall skew distribution in gender with female dominance. This unequal distribution with more females than males may be expressed by physiological, cosmetic or psychological reasons, as 15 of the 49 operated patients in Paper 1 were congenital or constitutional short individuals. Only 3 of the 15 patients were males. There is no rational reason to support the idea that a difference between sexes should exist and have influence on the results by use of the Ilizarov method.

Overview of age and gender

Paper	Patients N	Gender females/males	Age (years) median/average and (range)	
1	49	31 / 18	16 [a]	(4–48)
2	47	25 / 22	23 [a]	(4–59)
3	5	4 / 1	17	(16–21)
4	1	1 / 0	26	
5	7	3 / 4	3	(2–7)
Sum/average	109	64 / 45	18.3[a]	(2–59)

[a] Average

Diagnosis

The presented 5 papers consist of patients with various diagnoses.

In Paper 3 we report the results of lengthening young, healthy adults with no history of congenital or acquired deformities, while in Papers 4 and 5 all cases are congenital disorders. In Papers 1 and 2 the patients reported have a mix of many diagnostic categories. In theory healthy bone with normal soft tissue and bone stock should be the most easy to lengthen and reconstruct. According to Aldegheri et al. (1988) congenital or constitutional shortness are characterized by a normal or well developed muscular system. However, this was not found in the patients of Paper 3 with normal soft tissue envelope and bone stock. The high number of complications may be explained by the chosen method and not by the diagnosis of the involved patients.

The most difficult condition to treat with respect to bone healing should be the congenital pseudarthrosis of the tibia (CPT) (Inan et al. 2006). One of the factors which may contribute to this difficulty is the association with neurofibromatosis (Mb. Recklinghausen) which has been described to be present in the periostal tissue with missing neurons. Even if this disease is not malignant, it may lead to disturbance of the periostal contribution to bone healing (Sakamoto et al. 2007).

In the case report involving a patient with achondroplasia and slow bone healing, the short bone with a well developed muscular system should have contributed to a normal Lengthening Index (LI) and less complications regarding soft tissues (Aldegheri et al. 1988). However, the radiostereometric analysis (RSA) measurements performed at 6 weeks after end of distraction showed an axial deformation of the lengthening zone of more than 7 mm (corresponding to 15% global strain) during weight bearing. This high strain value is considered incompatible with classical theory of adequate stimulus for bone formation (Perren and Rahn 1980) and may explain the slow consolidation with the need of bone grafting.

In Paper 2 there was a nonsignificant difference in LI between lengthening with TSF and IEF. However, there was a tendency to difference between the two groups, and the reason may have been the high number of fracture sequelae in the TSF group, 12/20 versus 7/27. Malunions are often associated with a scary soft tissue envelope and hypotrophy of the muscles in the affected leg.

Deformity

Axial shortening is the only deformity parameter taken into consideration in all papers of the present thesis. However, in Paper 5 post treatment deformities are measured in detail. As far as we know, except for the degree of shortening, there are no reports in the literature about the influence of the various other deformities on the LI and complication rate. Also, in the current thesis LI has been calculated by time and lengthening distance only, without taking other deformity parameters into consideration. However, in all papers the preoperative goal of deformity correction was reached during the primary surgical procedure.

External fixator

All patients in this work have been operated with a ring fixator, either IEF with carbon fiber rings (Papers 1–5) or TSF with aluminum alloy rings (Paper 2). Frames with standard ring diameter sizes of both the IEF and TSF systems have been constructed. Usually rings with a minimal distance of 2 finger breadths (~ 3.5 cm) of free space circumferentially between the skin and inside of the ring have been selected (Paley and Tetsworth 1991). With both types of rings, Kirschner wires (diameter = 1.5 or 1.8 mm) have been utilized. Half-pins (diameter 4–6 mm) were applied with the TSF only. The possibility of using transverse Kirschner wires makes the device compatible and versatile regarding the size of fragments involved and stability of the fixed segment. The surgeon is less dependent on the anatomy and placement of the external device with respect to pin insertion and soft tissues.

Knowledge of the technique in three dimensional corrections and use of hinges are important factors to succeed in IEF deformity reconstructive surgery. By use of the TSF and the software program specially made for this hexapod device, no hinge construction is required, and over- or under-correction are easily adjusted for, if the preplanned adjustment does not succeed. With the TSF system and the Internet based software program (Taylor

2008), the surgeon is able to choose among 3 different methods during the operative application of the external device:

- Total Residual mode, which makes it possible to apply the rings first with respect to soft tissues and deformity without any preoperative planning
- Chronic mode, where the surgeon performs a preoperative deformity planning and reproduces the deformity in the frame before application of the TSF
- Residual mode, where the deformity correction does not succeed in the first place and an immediate secondary correction is necessary.

Overview of additional elements (wires, half-pins and nails) to the ring constructs of the applied external fixator frames

Paper	Fixation system	Kirschner wires in fragments n	Half-pins in fragments n	Intramedullary nail or wire n
1	IEF monofocal	Prox 3 Dist 4		
	IEF bifocal	Prox 3 Inter 3 Dist 3		
2	IEF monofocal	Prox 3 Dist 4		
	TSF	Prox 2 Dist 2	2 3	
3	IEF	Prox 3 Dist 3		Russel Taylor nail Ø = 8 mm n = 9 / 9
4	IEF bifocal	Prox 3 Inter 3 Dist 3		
5	IEF bifocal	Prox 3 Inter 3 Dist 3		Retrograde Ilizarov wire Ø = 1.8 mm n = 2 / 7

The speed and amount of axial correction is also easier to plan and perform exactly with ring fixators compared to monolateral fixators. Simultaneous lengthening and axial correction is very difficult to accomplish with monolateral devices and is almost always performed as a two-step procedure; acute axial correction and gradual lengthening distraction. This procedure is more easily performed in ring fixators with built-in simultaneous correction which is mathematically absolute correct in the TSF due to the software program. In biplanar deformities (valgus or varus and procurvatum or recurvatum) the monolateral device can be placed in the resultant oblique plane, but as mentioned above, most surgeons will usually prefer to correct the deformity in two steps. With the IEF the biplanar deformity is corrected in one step by hinges with the axis perpendicular to the oblique plane and at the level of the Center Of Rotation of Angulation (CORA) (Paley 2002). In the TSF, by use of a software program and the hexapod principles, origin of the reference segment and the corresponding point of the corresponding segment are brought together (Taylor 2002, Taylor 2007).

Even if the IEF and TSF have different mechanical characteristics when tested in identical configurations (Taylor 2002), we did not find any significant difference in LI and number of complications in Paper 2. With the use of 6 oblique struts (hexapod) the TSF is stiffer than the IEF in all the 3 cardinal planes. In addition the TSF was fixed to the bone with half-pins and wires, while wires only were used with the IEF frames. The overall difference in LI could implicate that a too rigid frame was of disadvantage and did not produce the micromotion which Ilizarov and other authors describe as optimal for bone healing (Claes et al. 1997, Gardner et al. 1997, Goodship and Kenwright 1985, Ilizarov 1992, Kenwright and Goodship 1989, Lanyon and Rubin 1984, Waanders et al. 1998). In our material, however, this difference in overall LI is more likely to be a result of low lengthening distance and the diagnosis leading to the reconstructive procedure. In the Ilizarov bone transport method the use of minimal fixation with 3 wires in the transport segment is beneficial to the soft tissues. The wires have to pull through the soft tissue envelope, and therefore an acute shortening of up to 30 mm is favourable. If the resected area is more than 30 mm, a traditional segment transport is necessary, because acute compression of the soft tissues may reduce the circulation (Josten et al. 1996). An intramedullary (IM) wire is inserted to guide the bone fragment into the docking area and to contribute with additional fixation. Even if the IEF frames were considered to be stable, the follow-up (Paper 5) showed axial residual deformity in all patients operated on with this method. Hence, the fact that all segments were intraoperatively axially aligned, did not prevent malaligment. Fibular pathology occurs in about 60% of CPT cases (Keret et al. 2000). The fibula was hypotrophic or even aplastic in all our cases, but one, which may be the main reason for the appearance of recurrent deformity in the late follow-up cases. The healing of the CPT converted the tibia into a condition similar to what we observe in fibular hemimelia which is associated with development of axial malalignment both in the proximal and distal tibia during the growth period (Catagni et al. 1991).

Lengthening osteotomy

Both tibia and fibula are osteotomized in most lengthening procedures. The only exception in our praxis is in tibial hypoplasia where the proximal fibula migrates proximally and needs to be pulled down simultaneously with the lengthening of the tibia. However, in the current thesis the specific role of the fibula per se and it's interference with the LI and complications have not been studied. In Paper 5 the recurrency of deformity is explained by a dysplastic fibula.

Level

The optimal level of osteotomy in simple lengthening by external fixation depends on many factors (Steen and Fjeld 1989), but is believed to be in the metaphysis and in the tibia preferably in the proximal metaphysis (Choi et al. 1999). This was the most used area for osteotomy in our cases. However, in simultaneous lengthening and axial correction the use of the CORA to define the osteotomy level is more simple to prevent to create a deformity with translation (Paley 2002). In bifocal lengthenings both the distal and proximal metaphysis are used. Our observation was that there was no difference in the LI regarding these two levels of osteotomies. However, in most cases we had to stop the distraction distally before proximally due to contracture of the ankle joint. As the external device was removed when both osteotomies were healed, the consolidation phase was calculated too long for the distal osteotomy.

Technique

The operative technique used in the proximal metaphysis was the standard Gigli saw method with percutanous application of the flexible saw (osteotomy). In the diaphysis and distal metaphysis a corticotomy with multiple drill holes and a straight or curved osteotome was used to preserve the medullar cavity and blood vessels (Ilizarov 1989). The fibula was obliquely osteotomized by use of an oscillating saw.

Intramedullary nailing

The combination of an IM nail and external fixator has been used for various reasons. Early removal of the external device is an obvious advantage as the patients' discomfort by use of a rather space-occupying frame leads to reduced mobility and decreased activity level. Reaming of the medullary cavity may lead to better results regarding healing even if the IM vascularisation is primarily disturbed (Paley et al. 1997, Shevtsov et al. 2004). However, the results in our patients show that slow bone healing and fractures of the internal device occurred. The rigidity of IM nails in rotation is characterized as low compared to intact tibia (Schandelmaier et al. 1996). The interfragmentary micromovement which is considered beneficial for the callotasis healing may with the use of IM nails, be transformed to macromovement which may lead to slow bone healing and development of pseudarthrosis (Klein et al. 2004). Stress related fatigue fractures of the internal device may be a result of this macromovement and increase the instability. In Paper 4 we used RSA to demonstrate a rather large movement between the bone fragments across the lengthening callotasis zone. In the examined patient slow consolidation was observed and bone grafting was necessary to achieve bone healing.

In our Lengthening Over Nail (LON) cases we observed one deep IM infection which is a major complication and may in some cases lead to amputation. This major problem, however, was not observed in our 2 cases with CPT operated on with an inserted IM wire to lead the transport segment into the docking zone distally. The wires used in these cases were only with a diameter of 1.8 mm which did not interfere with the wires connected to the IEF and probably did not disturb the IM vascularization or endosteal bone formation (Paper 5). In the lengthening cases (Paper 3) additional reaming was nessesarry to allow the IM nail with a diameter of 8 mm to slide with limited friction. This extensive reaming disturbs both the endostal morphology and IM blood supply (Bong et al. 2007) and is therefore a risk factor for bacteriae to infect the IM cavity through the entrance portals caused by pins and wires. Reaming may also leave bone sequesters in the cavity which is a well known risk factor for bacterial infection and may reduce the ability for antibiotics to prevent or treat osteomyelitis. All patients with LON in Paper 3 were operated on the tibia. The soft tissue envelope surrounding these segments is characterized by a thin skin and subcutaneous fat barrier at the antero-medial aspect of the bone. The short distance for bacteriae to migrate and the relatively low vascular supply of fat tissue may be factors which explain why the tibia is a high-risk bone to lengthen with the use of the LON technique.

Lengthening process

A total lengthening process may be divided into 3 periods;, "distraction" (included 7 days of latency), "consolidation" and "rehabilitation". However, in our papers the rehabilitation period is not specificly included, and we have found it most reasonable to use only 2 periods; the "distraction phase" and the "consolidation phase". These 2 phases are not used to define single indices, but add to a sum which describes the total time from operation until at least 3 cortices are observed on biplanar radiographs. The calculation of this time period (months) didvided by the lengthening distance (cm) results in the LI. This term was first introduced by Paley (1990) and is well known and makes it easy to compare our own papers and also make comparisons possible between our results and the results presented by other authors.

Distraction phase

The patients were controlled at the outpatient clinic with 2 weeks intervals during this period. All patients included in this thesis are followed during the distraction phase with a standard distraction rate of 1 mm pr day in monofocal osteotomies and 1.75 mm pr day in bifocal osteotomies, distributed into 1 mm in the proximal metaphysis and 0.75 mm in the distal metaphysis. The soft tissues and especially the nerves may result in chronic damage by a too rapid lengthening. In fracture situations healing is well known to be problematic in the distal tibia (Ristiniemi 2007), hence we have chosen to reduce the amount of daily lengthening in the distal metaphysis. Just as the daily rate of distraction, the rhythm is performed in the same way in all tibias with 4 times 0.25 mm lengthening in patients with a daily distraction rate of 1 mm and 0.25 mm 3 times per day in zones with 0.75 mm daily distraction rate. The distraction is performed with approximately 4–6 hours intervals between each manoeuvre.

In our material we did not observe any difference in the healing rate between the two levels of the osteotomies with different rhythm of daily distraction. The evaluation of this observation, however, is not accurate because in most cases of bifocal lengthening the distal distraction was ended before the proximal distraction due to soft tissue complications such as contracture of the joints or pain.

Consolidation phase

The interval between outpatient controls was 6 weeks during the consolidation phase.

We did not change the treatment protocol with respect to weight bearing during this period, as full weight bearing was allowed during both the distraction and consolidation phases, with exception of the LON cases that were allowed full weight bearing 2 weeks after frame removal. The consolidation phase was ended when at least three cortices were observed on biplanar radiographs. All patients, but the LON cases, underwent a cast period of 6 weeks after removal of the frame and before start of the rehabilitation program. In proximal lengthening osteotomies of the tibia we included both the knee joint and the ankle joint in the cast, while distal tibial callotasis had a lower leg cast applied. The CPT cases continued to protect the tibia by use of an orthosis until skeletal maturity.

Radiography

To evaluate the different kinds of deformities we have used three standard radiographic assessments:

- Long standing x-rays with patella centered in the frontal view and 90 degrees to this projection in the lateral view. The deformity parameters have been evaluated according to the CORA method (Paley 2002)
- The LLI has been evaluated radiographically by orthoroentgenography (Green et al. 1968, Tjernstrom et al. 1996). Recent reports by Sabharwal et al. (2006, 2007) demonstrate that long standing x-rays are reliable for assessment of LLI in addition to evaluation of angular axial deformities.
- Rotational deformities were made visible by CT (Reikeras and Hoiseth 1989).

All objective findings were controlled by clinical examination. Joint contractures and congenital deformities may lead to difficulties in correct evaluation of anatomical axes. In our opinion clinical deformity parameters may be more important than objective radiological measurements. To avoid over- or undercorrection, rotational deformities and recurvation/procurvation deformities were clinical evaluated in particular.

At the end of distraction, new long standing x-rays were performed to see if the planned correction had been achieved. During the consolidation phase plain x-rays were examined in the frontal and side views. We considered the callus formation to be mature if 3 cortices were observed on x-rays in two planes, or if the callus was evenly distributed through the complete lengthening zone.

Even if objective evaluation of the maturity of the regenerate can be performed by established methods as dual-energy x-ray absorptiometry (DEXA) and ultrasound (Bail et al. 2002, Maffulli et al. 1997, Maffulli et al. 1999, Young et al. 1990), we prefer to use mechanical testing by load-share measurements (Aarnes et al. 2005b, Aarnes et al. 2006) as supplemental information to biplanar plain x-rays.

The special equipment used for RSA assessment of micro movement (Paper 4) and theory behind the method is referred to in the thesis from 1974 by Göran Selvik, the inventor of the method (Selvik 1989). According to Valstar et al. (2005) more than 5000 patients with inserted tanatalum beads have been included in several RSA studies and more than 300 scientific papers have been published. According to J. Kärrholm (personal communication June 5, 2008) the number of patients with inserted beads may be as high as 10.000–15.000, but to our knowledge not a single report of any side-effects exists.

Lengthening index

The total treatment time is of great importance both to the patients and the persons involved in the treatment and rehabilitation of the patient. External fixation time describes the period the patient is treated with an external fixator. The time in the external fixator is actually what really matters for the patient, but scientifically this term is not exact enough in comparing different methods. An example is shown in Papers 1 and 2 versus Paper 3, where the time in the external fixation differs between patients operated with external fixator only and patients operated on with the LON technique. The treatment time from operation of the extremity to the time of consolidated callotasis zone with no need of further external or internal support, is not explained with the external fixation time, but with the LI term.

In bifocal osteotomies there are 2 zones of callotasis which differ both in distraction rhythm, length of distraction gap and time of distraction. In Paper 1 the distraction phase is not used because the bifocal cases differ in daily distraction rate from cases with monofocal lengthenings. In bone transport (Paper 5) the LI may be unspecific, because the readers or authors may mix the time from start of treatment to healing of the docking site with the healing of the callotasis zone. In all our patients observed in Paper 5 the docking zones were evaluated as healed before the lengthening zones. In addition, due to pain, bad bone regenerate or contracture the speed may be temporary or permanently reduced. In conclusion, the best, most precise and most comparable factor was the LI, expressing time (months) in the external fixator divided by the lengthening distance (cm).

Age is a factor which influences the treatment time (Fischgrund et al. 1994). In Paper 2 the age

Overview of lengthening distance and index

Paper	Patients (N)	Gained length median/average and (range) (cm)	Lengthening Index median/average and (range) (months/cm)
1	49	5.8 [a] (2.4–10.0)	1.4 [a] (0.7–4.4)
2	47	3.6 [a] (0.5–7.0)	2.7 [a] (0.8–8.4)
3	5	7.0 (5.5–7.3)	4.4 (2.4–6.1)
4	1	5.1	4.1
5	7	5.4 (2.6–7.5)	1.7 (0.8–2.7)
Sum/average	109	4.9 [a] (0.5–10.0)	2.2 [a] (0.7–8.4)

[a] Average

factor was adjusted for by ANCOVA. The average LI in Paper 2 for all lengthenings between 2.4 and 6.0 cm was found to be 2.0 months/cm. In 8 cases reported in Paper 3 the average LI was 4.3, which is high compared to other monofocal cases. The patients with constitutional shortness did not have a specific skeletal disease and the lengthenings ranged from 55 to 73 mm, which should be expected to result in a low LI. Also the age of these patients ranging from 16 to 21 years is optimal for fast healing. However, the influence of the IM nail which causes disturbance of endosteal healing may explain this observation.

In the CPT cases the median LI was 1.7 months/cm with a median callus distraction length of 54 mm, which is higher than the LI of the mixed cases in Paper 1. Even if the median age of the CPT cases was lower, the presence of pathological fibrous nerve tissue in the affected limb segments with CPT, may explain the observation of slow healing.

Complications

We did not observe any intraoperative complications, but in the distraction and consolidation phases they were rather frequent. Most of the complications were registered as minor and were treated without hospitalisation. More joint contractures were observed in the tibias with bifocal lengthening which is explained by the rapid lengthening rate of 1.75 mm pr day compared with 1.0 mm pr day. More delayed unions and nonunions needing bone grafting were observed among smokers, elderly patients and malunions. Most of these cases were adults, and previous trauma and treatment may have influenced both bone morphology and the quality of the soft tissue envelope. Sequelae after fractures usually result in deformities combined with a moderate shortening. Both Papers 1 and 2 show that a small lengthening distance is associated with high LI and the consolidation phase is therefore relatively long and may have led to “premature” bone grafting in some cases. In cases with lengthening over an IM nail, both extensive reaming and inadequate internal fixation may be the reason why slow healing occurred. Minor complications were experienced in all procedures where callus distraction was used as method and there were no differences between age, sex or ethiology.

Post treatment deformity occurred in all patients with the CPT diagnosis. They all developed angular deformity, and one explanation of this occurrence could be the dysplastic fibula which was present in all, but one case. CPT is known as a condition of dysplastic tibia, and after the successful treatment of this condition with healing of the bone and equalization of the LLI, the condition may be considered as a transformation into fibular hemimelia, which is characterized as a short leg with axial malalignment.

Statistics

In Papers 3–5 less than 10 patients and/or segments were included. Hence, due to these small numbers in each paper, statistical analysis could be performed in Papers 1 and 2 only. Depending on the number of observations, both parametric and nonparametric distribution statistics were used with central observations expressed both as average (arithmetic mean) and median. Dispersion was expressed both as standard deviation (SD) and range (minimum – maximum). Differences were evaluated by analysis of variance (ANOVA) and adjustment for age differences by analysis of covariance (ANCOVA). A p-value < 0.05 was considered statistically significant.

With help from a professional statistician in Papers 1 and 2 data from comparable groups were entered into a multiphase best-fit model for graphical illustration and were presented as quadratic-linear function curves estimated from a maximum likelihood method.

As 27 patients with 27 monofocal tibial osteotomies from Paper 1 also were included in Paper 2 for comparison, the present thesis is based on a net number of 82 individuals, 48 females and 34 males, 100 tibial segments and 133 osteotomies. In Paper 1 there were 4 bilateral procedures among the 31 monofocal lengthenings. In Paper 2, to avoid problems with dependent observations, only the first operated leg was included in the analysis for the 4 patients in question with bilateral procedures among the 27 patients with monofocal tibial lengthenings.

We discovered and learned in retrospect that the statistical issue concerned with independent observations had not been handled completely correct in Paper 1, where bilateral operations were treated as separate observations. Revision of the statistics using a Mixed Model analysis (Statistical Analysis System; SAS version 9.1.3; Cary, North Carolina, USA) with all the bilateral lengthening patients included (4 monofocal and 10 bifocal) did not have any significant influence on the results: We had a dataset with 63 measurements measured on 49 different subjects. The applied Mixed Model analysis of variance allows for multiple measurements on some (or all) of the subjects. The fitted Mixed Model will have identical means to the fixed effects situation (where the 63 measurements originally were incorrectly seen as independent), but the estimation of the dispersion takes into account that just 49 subjects were included and this will in turn effect the p-value. The adjusted and correct p-value for the difference between groups was $p = 0.003$.

General discussion

Patients

In our work we present a net number of 81 patients with 100 segments and 133 osteotomies on the tibia. Other authors report their results with a comparable number of tibial segments operated. Maffulli et al. (1996) reviewed retrospectively 281 lower limb lengthenings involving 146 tibial segments in 130 patients with focus on complications, Lengthening Index (LI), osteotomy technique and aetiology. Noonan et al. (1998) reviewed 147 tibiae among 161 lower limb lengthenings using monolateral external fixator. Their retrospective analyses comprised age and diagnosis of the patients, time from operation to start of distraction (latency), distraction time, consolidation time and complications. Aldegheri (1999) and Aldegheri with collaborators (1989) presented in 2 papers the results with the use of monolateral tibial devices. In the first paper from 1989 they focused on the method described by Ilizarov and the results in 124 tibiae and 146 femorae with respect to complications, lengthening distance and healing index. In the second paper, however, Aldegheri compares 3 different methods with 3 different devices, all monolaterals, used in lengthening procedures. Fischground et al. (1994) reported 114 lower-extremity lengthening procedures using the Ilizarov External Fixator (IEF). The material comprised 97 tibiae and focused on corticotomy level, age and distracted gap.

Our material consists of more female cases than male cases, 64 versus 45, respectively, with most of the difference found in Paper 1. This paper comprises several patients (15/49) with constitutional shortness or achondroplasia undergoing bilateral tibial lengthening. The main indication for lengthening in these cases was to achieve increased body height. Our experience is that female persons are more sensitive to short stature and therefore more motivated for this long lasting, painful and complicated procedure. Aldegheri et al. (1988) reviewed 72 patients with achondroplasia or hypochondroplasia, where the difference in number between genders was less, but still with female patients in majority. However, both Cattaneo et al. (1988) and Catagni et al. (2005) from the Lecco Institute, reported more males than females in their experience with bilateral tibial lengthening by use of the Ilizarov method in patients with short stature. To our knowledge different results in lengthening procedures between females and males have never been reported.

In accordance with most of the leg lengthening papers published (Aldegheri and Dall'Oca 2001, Dahl et al. 1994, De Bastiani et al. 1987, Maffulli et al. 1996, Manner 2007), the majority of patients in the current thesis are young individuals, as the average age is 18 years with a range from 2 to 59 years at the time of operation. Hence, many of the patients are growing individuals and many have been operated because of congenital disorders. This will most likely have had an influence on our results, as treatment time and rate of complications are dependent on age and diagnosis (Maffulli et al. 1996).

The smoking habits of the patients have been alluded to as an important negative factor with respect to bone healing in DO (Paper 2). Recent scientific publications from animal experiments support the fact that nicotine from cigarette smoking causes vasoconstriction and ischemia and has a direct inhibitory effect on osteoblastic cells which results in delayed mineralization during the bone healing process of the regenerate (Ueng et al. 1999, Zheng et al. 2008).

Diagnosis

In our case report (Paper 4) focusing on radiostereometric (RSA) measurements, we observed slow bone healing in an achondroplastic patient. Other authors report good LI in lengthening of the tibia in patients with this diagnosis. Cattaneo et al. (1988) lengthened 42 tibial segments in 21 achondroplastic patients with use of the IEF and presented excellent results both regarding LI and rate of complications. Both Aldegheri et al. (1988) and

Aldegheri (1999) reported the results of lengthening in achondroplasia comprising 49 and 58 tibae, respectively, operated with callotasis and monolateral fixator. In accordance with other authors they report good results both regarding healing and percentage of complications. We assume that our case may not be representative for the usual outcome in lengthening of achondroplasic patients, due to the mechanical properties of the IEF, and the results found in our paper are therefore discussed later with respect to frame construction. Constitutional shortness was the diagnosis of the 5 patients with 9 tibial segments operated on with the Lengthening Over Nail (LON) technique in Paper 3. Except for 2 recent papers (Kocaoglu et al. 2004, Watanabe et al. 2005), no other reports, to our knowledge, have been published with the combination of this technique in the tibia and the short stature diagnosis.

Congenital pseudarthrosis of the tibia (CPT) is a very rare condition with an incidence of around 1:190000 (Traub et al. 1999). Our study of 7 patients in Paper 5 includes a small number, but with exception of the CPT papers based on the multicenter study organized by the European Paediatric Orthopaedic Society (EPOS), only a few cases are also involved in other studies (Inan et al. 2006, Ohnishi et al. 2005). However, the EPOS study has resulted in several publications dealing with the CPT diagnosis (Grill et al. 2000, Hefti et al. 2000, Ippolito et al. 2000, Keret et al. 2000, Romanus et al. 2000, Tudisco et al. 2000, Wientroub and Grill 2000), including reports of the results in patients operated with the Ilizarov bone transport method (Grill et al. 2000, Wientroub and Grill 2000).

The current thesis does not include patients with acquired nonunions, but malunions with the combination of lengthening and axial correction are represented by 10/49 patients in Paper 1 and 19/47 patients in Paper 2. Other authors who present their experience with lengthening of the tibia report similar distributions. Aldhegeri (1999) presents 230 tibial lengthenings with 34 acquired conditions as indication for operative deformity correction. Choi et al. (1999) reports on bifocal lengthening with 8 out of 43 procedures performed on malunions or sequelae after infection. Stanitski et al. (1996) presented their result on tibial lengthenings with the IEF. As for the other papers mentioned they have a smaller number of aquired conditions treated (9/62) compared to congenital disorders.

External fixator

An extensive overview of the biomechanics of external fixation and limb lengthening is presented in a recent review article by Younger et al. (2004) where detailed information of biomechanical characteristics of external fixators and the Ilizarov technique is included.

The most important capability of an external fixator is a flexible design that can adapt to the anatomy for fixation of the various parts of the human body. In addition, the complete external frame construct must accomplish adequate mechanical stability to create environmental conditions compatible with a pronounced biological response and efficient healing process. We have chosen an external ring fixator in all studies of this thesis to secure maximum control and optimal versatiltity.

The ideal characteristics of a ring fixator with ability to accomodate variable stiffness to optimize the healing process at all stages of treatment should according to Watson et al. (2000) be:

- maximum off-axis rigidity to prevent rotational, torsional and shearing motion at the fracture/osteotomy site;
- controllable and variable axial stiffness for management of the degree of interfragmentary motion (IFM) during all stages of treatment;
- minimum soft tissue damage due to wires and pins;
- maintenance of strength and stability for duration of treatment.

An assembly of individual modular components creates a complete frame construction with various configurations depending on the number of rings and wires in addition to the longitudinal elements (Ilizarov 1990). The importance of understanding the effects of individual components for appropriate frame constructions and the global stiffness characteristics of the frame was noted by Kummer (1992). In an external ring fixator the purpose of the ring structure is to distribute the stress as evenly as possible, to maintain the wire tension and to distribute the load from the wires and pins to the longitudinal elements. Altering the ring size changes the wire span and the effective stiffness of the tensioned wire with the result that the overall frame stiffness increases with a decrease in diameter. Ring material of Aluminum is stiffer than carbon composite (Kummer 1992), but the material in a ring frame construct makes no difference to overall frame stiffness in the various modes of testing (Bronson et al. 1998). The carbon fiber ring is light in weight, with improved comfort to the patients and the rehabilitation program may be more easy to accomplish (Nele et al. 1994).

Simple threaded rods and complex hinged distraction assemblies comprise the 2 types of longitudinal element supports. No studies on the effect of altering the number of longitudinal elements or their placement around the circumference of the ring exist. Adequate stability with tensioned wires requires at least 3 longitudinal elements, and also secures involvement of all elements and a more uniform distribution of the load compared to use of 4 elements, where one of the rods may not be involved in load-sharing at all (Waanders et al. 1998). In the Taylor Spatial Frame (TSF) 6 oblique struts are mandatory in predefined positions and the complete frame becomes unstable in all directions if only one of the 6 struts is removed (Taylor 2002). In a brand new publication Henderson et al. (2008) point to the conformational instability of the TSF which occurs when the frame's configuration requires short struts and results in ring-strut angles less than 30 degrees. This is a critical factor well known from truss mechanics and at angles of this magnitude and smaller the frame stability is significantly compromised in compression and bending. Hence, adequate strut lengths should be chosen in construction of a TSF to avoid too small ring-strut angles in deformity corrections. Also, a displacement offset of 25 degrees between the 2 rings of the TSF will result in some minor instabilities. A critical comment to this paper may be that the TSF frame was tested "passively", i.e "as it is" without any preload which may add to it's stability in the clinical situation.

The optimal biomechanical environment for healing of a lengthening osteotomy is not known. However, a wide range of IFM obviously exists and it is assumed that a relatively wide, but still more specific and narrow range of IFM promotes healing (Gardner et al. 1997). The classical IEF design with wires only or modified by use of half-pins has been used by many authors working with the Ilizarov method (Catagni et al. 2005, Ilizarov 1992, Paley 2002). The special properties of the dynamic and flexible classical IEF during loading have been described as the 'micromovement' or 'micromotion' effect which is considered to be favourable with respect to bone healing (Bronson et al. 2002, Kershaw et al. 1993, Wolfson et al. 1992). Whether the deformation of pins and other elements of the external frame during weight bearing and physiological conditions is within the elastic range, has been a subject of debate (Podolsky and Chao 1993), and some authors found only pure elastic properties (Aarnes et al. 2005a, Waanders et al. 1998). Use of half-pins improves the stiffness (Paley et al. 1990), and through the recent years there has been a clear tendency towards mounting of stiffer frames by application of more half-pins at the sacrifice of wires (Catagni et al. 2005, Green et al. 1992). A modern concept is to increase the rigidity of the external fixator by replacing tensioned wires with half-pins on each side of the bone gap. According to Yang et al. (2003) this results in frame stiffening under increasing axial load, inversely correlated to the number of wires. On each side of the distraction gap the number of wires should be at least 4 in a 2-ring frame regarding bending stiffness (Ilizarov 1990). Three versus 2 half-pins increases the axial stiffness by 6 (4–7) N/mm and an offset screw (e.g a Rancho cube) with 2 half-pins increases the axial stiffness by 20 (12–26) N/mm. Hence, these reinforcements are recommended for high loads in bone defects and lengthening (Yang et al. 2003). Positioning of the wire crossing angle close to the osteotomy site is one of the most influential variables on the overall frame bending stiffness, along with the axial distance between rings of each fragment. Wire crossing angles less than 45° are less stable in flexion than wire crossing angles of about 90° which is optimal to prevent low bending stiffness and also increase the translational rigidity (Ilizarov 1990, Podolsky and Chao 1993). However, the torsional rigidity increases the further the crossing angle is from 90° (Waanders et al. 1998, Wu et al. 1984). Hence, ideally a balance of the crossing angles between 45°–90° should be achieved. By application of the LON technique both monolateral external devices with half-pins and ring fixators with wires. However, due to the small amount of space available for inserting half-pins after IM nailing, thin wires in combination with a ring fixator has been preferred (Watanabe et al. 2005).

In the 5 papers comprising the present thesis the above described basic principles of external fixation by use of ring fixators have been followed to optimize the conditions during the Ilizarov method process. According to our increasing knowledge and experience through the years the equipment and procedures have changed on the way. The original Ilizarov ring made by stainless steel, was later modified to carbon rings by producers in the Western world and to the TSF which is made by aluminum alloy. The IEF used in the present thesis was constructed with 3 rings both in monofocal and bifocal lengthening osteotomies. In bifocal procedures each ring was connected to the bone with 3 wires. In monofocal lengthenings the metaphyseal ring was connected to bone with 3 wires while the 2 other rings had 2 wires each, respectively. With respect to the above discussion the metaphyseal ring may have been applied to the bone with a minimum number of wires to create optimal stiffness. In Paper 4 objective measurements by use of the RSA method demonstrated a global axial deformation of 7 mm (15%) across the lengthening zone. This IFM value was high and may be the explanation of the observed slow bone healing. According to various authors the optimal degree of axial micromotion can be within a wide range of microns (Claes et al. 1997, Gardner et al. 1997, Goodship and Kenwright 1985, Kenwright and Goodship 1989, Lanyon and Rubin 1984, Waanders et al. 1998, Wolf et al. 1998). The size of the fracture gap represents an important contributory factor to the ideal displacement amplitude (Claes et al. 1997), and the strain amplitude (displacement as % of fracture gap size or analogue length of callotasis zone) is the key factor. By combining various findings the ideal strain amplitudes should be between 0.5–45%, which is a degree of motion commonly seen in humans (Gardner et al. 1997).

Lengthening osteotomy

Noonan et al. (1998) did not find any differences in healing index or complications between proximal metaphyseal and diaphyseal lengthening osteotomies in the tibia. Fischground et al. (1994) reported higher LI in diaphyseal lengthenings. However, they also reported that this difference was not present in lengthenings of more than 7 cm. Choi et al. (1999) reported that a higher LI value has to be expected in the distal callotasis compared to the proximal in bifocal tibial lengthenings. The authors presented these findings both in small lengthenings, but also in lengthenings of more than 4 cm. They suggest that the distal distraction speed should be ¾ of the proximal, which also is the case in our studies in Papers 1 and 2. However, our distraction rate in bifocal lengthenings is based on clinical experience. In addition to pain we observed transient nerve palsy and ankle joint contracture by a daily distraction rate of 1 mm both in the proximal and distal callotasis zones. These observations resulted in an earlier stop of distraction in the distal zone compared to the proximal distraction. We did not register any obvious differences in complications between patients operated with monofocal proximal versus monofocal distal metaphyseal osteotomy, but these few cases (TSF n = 4; IEF n = 3) were not analyzed specificly for comparison.

In our study we used two different types of osteotomy techniques. In the proximal tibial metaphysis we routinely use the Gigli saw method (Paley and Tetsworth 1991) while we in the distal metaphysis used the combination of drill hole corticotomy and osteoclasis (Schwartsman and Schwartsman 1992). We did not observe any difference in LI or complication rate between these two methods. The reason to choose two different osteotomy techniques is based on clinical experience and the easiness to avoid soft tissue injuries at the different localisations. Ilizarov demonstrated in animal studies that the preservation of the IM cavity was essential for rapid bone healing in DO (Ilizarov 1992). However, Kojimoto et al. (1988), found that it is more important to preserve the periostium than the endostium. The same results were presented by Delloye et al. (1990). The theory of these findings were supported and explained by studies performed back in 1973 by

Rhinelander (1998). They demonstrated a tremendous capacity for repair of structures in the medullary channel already 6 days after injury. The latency period after osteotomy before start of distraction is 7–14 days, and at this time the IM vessels are regenerated (White and Kenwright 1991). The endostium, however, may have less regenerative and reparative potential (Paley and Tetsworth 1991). The terms corticotomy and osteotomy are used in the literature as separate procedures, but the exact meaning of these terms which are supposed to differ with respect to salvage of the IM vessels with advantages by use of corticotomy technique is questionable. However, the oscillating saw which produces heat and plugging of the bone channels (Paley and Tetsworth 1991) is rarely used in lengthening procedures. Frierson et al. (1994) showed significant delay in bone healing by use of oscillating saw in an animal study. Eralp et al. (2004) showed in a study which compared Gigli saw and drill hole osteotomy that Gigli saw produces a better callus formation in lengthening. The reason for this is explained with the better preservation of the periostium. We have not been able to confirm this in our studies. Paktiss et al. (1993) observed less pain in 2 patients with the use of Gigli saw compared with these patients' previously experience with corticotomy. We did not perform any systematic registration of these findings in our patients. Sen et al. (2002) showed that clinical experience is of great importance to perform Gigli saw osteotomies. Nerve and muscle injuries were common in a group of residents and inexperienced consultants who operated on cadavers and produced 10 injuries in 42 procedures. To make the drill hole osteotomy easy Yasui et al. constructed a drill guide and demonstrated the results and technique in a paper published in 2000. Tjernström (1994) in his thesis "Leg Lengthening" compared 3 different surgical lengthening techniques; direct lengthening, lengthening by the Wagner method and callus distraction lengthening. Of the 3 reviewed techniques callus distraction was found to be the safest and the one method recommended.

Lengthening over nail

By combining external lengthening and IM nailing in the LON technique, it is obvious and not surprising that the time with use of the external device decreases. Huang in 1997 found that the treatment time was significant shorter by use of LON and that the complications were relatively few. However, the LI was increased in our 9 segments operated on with this method in Paper 3. Watanabe et al. (2005) reported no difference in callus formation between traditional lengthening with the Ilizarov method compared with the LON technique in tibial lengthening. Shevtsov et al. (2004) reported increased bone formation with the use of LON, both in animal studies and in a clinical observation.

The complication rate due to the external device seems to be lower by use of LON (Watanabe et al. 2005), but Simpson et al. (1999), concluded in their study on 18 femoral and 2 tibial lengthenings that deep IM infection and osteomyelitis may occur more frequently than by use of traditional lengthening technique. Kocaoglu et al. (2004) reported 6 complications in 7 tibial segments, among them 1 osteomyelitis and 1 slow bone healing requiring bone grafting. This is in accordance with our experience. We observed slow bone healing in the anteromedial aspect of the tibia which also Lin et al. (1996) reported in their series of 15 tibial lengthenings with the LON method. In the same paper they reported 1 case of osteomyelitis. By fixation with an IM nail screw or IM nail, breakage in the consolidation phase is not only observed in tibial, but also in femoral lengthenings. Paley et al. (1997) observed 2 implant breakages (1 interlocking screw, 1 IM nail) in their series of 32 lengthenings.

Our conclusion was that we did not recommend the method used in the tibia. This is also expressed by Simpson et al. (1999), but only as a precaution. Lately a new technique with the purpose of reducing the time in external fixator has been presented. After the distraction phase, the external fixator is exchanged with an internal plate or nail. Iobst and Dahl (2007) reported promising results with this technique with no infections associated with the method. Lengthening nails with no use of an external distraction device show promising results in case reports, but is associated with hardware failures and unsatisfactory achievements of longer lengthenings (Baumgart 2008, Hankemeier et al. 2004, Paley 2007).

Reaming of the IM channel is supposed to destroy the endostal bone healing and therefore increase the LI. This was not observed by Shevtsov et al. (2004) who found increased bone healing, even premature consolidation with the use of LON. Our observations together with the findings of Lin et al. (1996) show that the anteromedial aspect of the tibia is the slowest consolidation area. This is also the area with the smallest soft tissue coverage. These reports may support the theory that endostal bone healing is of less importance in callus distraction.

Distraction rate and rhythm

The daily distraction rate is of great importance to the result following leg lengthening. There are two factors which are to be taken into consideration; osteogenesis and soft tissue adaptation. Early observations done by GA Ilizarov (1989) demonstrated that 1 mm is the optimal rate of daily lengthening, at least with respect to new bone formation. This observation has not been changed over the last 50–60 years and has been shown in animal studies to be correct (Li et al. 1999). The authors investigated the angiogenesis response at 4 varying rates (0.3, 0.7, 1.3, 2.7 mm/day) in rabbits. They observed that maximally stimulation of the neoangiogenesis at the central fibrous lengthening zone occurred at rates of 0.7 and 1.3 mm pr day, while rates of 0.3 and 2.7 did not optimally stimulate this new formation of angiogenetic tissue. In all our patients included in the current thesis the distraction rate was set to be 0.75 to 1.0 mm pr day, depending on procedure and level of osteotomy. The rhythm was routinely 0.25 mm 3–4 times a day, which is the rate observed to be optimal. More reports have been published on the soft tissue adaptation with respect to rhythm of the daily distraction. The most common distraction rhythm is told to be 0.25 mm four times a day, but by increasing the rhythm rate with many repetitions of small increments, the soft tissue envelope is less damaged during the lengthening. Ilizarov (1989) showed in an animal study of 120 dogs that the greater the distraction frequency, the better the outcome. Shevtsov et al. (2001) showed that automatical high frequency lengthening in 78 human cases provided optimal conditions for tissue regeneration with decrease of the treatment period. In an animal study of rabbits Shilt et al. (2000) showed that range of motion (ROM) of the ankle joint was far better in the animals operated on with 1440 increments pr day compared with 3 daily increments. Makarov et al. (2001) showed that the preservation of muscle fibres was far better in 46 goats distracted in the tibia 720 times a day compared to distraction 1 or 5 times per day. Mizumoto et al. (1996) found that an increase in distraction frequency may promote DNA synthesis in the rabbit muscle which provides better muscle accommodation. Reduced ROM with increased daily distraction rate was found to be caused by perimysial fibrosis with increase of collagen Type 1 rather than the muscle fiber per se (De Deyne et al. 2000). Aarnes at al. (2002) showed in a unique clinical model in two patients operated on with simultaneous bilateral tibial lengthening, that the tensile forces in the tibia distracted with high frequency distraction were significantly lower compared to the leg distracted with low frequency. Shevtsov and Popkov (2002) observed lower LI in 406 segments distracted 60 times a day compared to about 4500 segments distracted 4 times a day; all segments had a total rate of 1 mm a day. Mizuta et al. (2003) observed better callus formation on the leg with high frequency distraction in chickens operated on bilaterally with daily inclination of 2 versus 120 times on each side, respectively.

In Paper 1 we presented more joint contractures in bifocal lengthenings than in monofocal which may be the result of a higher overall daily lengthening rate. We recommend 0.75 mm pr day at each osteotomy site and inclusion of the ankle joint in the frame.

Weight bearing

With exception of the patients operated on with the LON technique in Paper 3, full weight bearing was permitted from the first postoperative day. However, most patients used crutches and did only partially weight bear. A certain degree of IFM during loading of the lengthening zone in the distraction and consolidation phases may contribute to increased callus formation. Compression stress across the osteotomy site exerted by weight bearing initiates osteogenesis in DO (Leung et al. 2004). Goodship and Kenwright (1985) showed in a sheep fracture model that induced IFM improves healing. The same authors with collaborators published results on micromovement in 80 human tibial fractures which showed more rapid healing when the fracture was stimulated with axial compression/distraction of 1 mm at a frequency of 0.5 Hz during 20 minutes daily for 3 weeks at the maximum (Kenwright et al. 1991). This clinical observation was also reported in a paper from Fink et al. (1996) where 58 callus distractions in humans were followed with focus on various parameters. In their study, young age of the patients and a high degree of loading were the most important factors to increase the callus formation. In addition, the mechanical properties of the frame are of great importance with respect to healing, and in our Paper 4 we observed axial movement of 7 mm in a partial weight bearing situation, which may have contributed to slow bone healing. In the present thesis different frame configurations have been used. Based on our experience, we have changed the routines from frames constructed with 3 rings and 2–3 wires on each ring to more stiff constructions with 3 rings and inclusion of at least 2 half-pins on each fragment. Furthermore, we include the foot in the frame in bifocal lengthenings to prevent ankle joint equinus contracture (Paley 1990).

Dynamization

Dynamization of the callotasis zone may be performed in different ways. In monolateral lengthenings de Bastiani introduced a method where the patient in the outpatient clinic had the frame unlocked, and thereafter relocked after some weight bearing steps (De Bastiani et al. 1986a, Price and Mann 1991). Later on the Orthofix® company introduced a silicon ring (Dynaring) which allowed dynamization without the risk of collapse of regenerated new bone. Pouliquen et al. (1994) and Glorion et al. (1996) showed in clinical observations that the silicone dynamization was better compared to the original De Bastiani method. Our personal experience by using monolateral devices is that the dynamization is difficult to monitor because the telescopic mechanism is stucked in many cases, possibly due to increased friction forces combined with high bending moments.

The ring fixator may be dynamized in 3 different ways; by pin removal, by telescoping dynamization devices or by reducing the tension forces in the apparatus monitored during assessment of regenerate axial stiffness by load-share measurements (Aarnes et al. 2005b). Claes et al. (1995) demonstrated significantly increased callus formation after telescopic spring dynamization in a sheep model with a ring fixator. However, to our knowledge, there are no articles presenting results of dynamization in human callus distraction with ring fixators. At present we use force and load-share monitoring as a guide to dynamization, and we are able to fully or partially dynamize the ring apparatus in the axial direction.

The compression-distraction (accordion) manoeuvre (Kummer et al. 1990) can be mistaken with the dynamization procedure. However, this method includes a progressive daily shortening followed by the same amount of daily re-lengthening. In a recently published experimental study in sheep Claes et al. (2008) demonstrated that slow temporary distraction of 0.5 mm twice daily for 2 days with subsequent compression of 1 mm twice the 3rd day repeated 4 times of a diaphyseal osteotomy significantly accelerates bone formation and healing rate of the osteotomy. In our opinion dynamization is an active intervention synonymous with gradual destabilization of the frame (Younger et al. 2004), either performed by reducing the pretension (distraction force) or by removing wires and/or pins (Yang et al. 2003).

Lengthening index

We find the LI term most useful and think it describes the treatment period at the most accurate because it comprises the total and longest observation period which is definitely defined. The decision of frame removal is partially subjective and also dependent on several practical factors like the variation in interval between outpatient controls with x-rays, booking of operating theatre, individual preferences etc.

In our opinion daily distraction rate and rhythm are more specific and informative parameters than use of the term distraction index (distraction time divided by lengthening distance) (Shevtsov and Popkov 2002). Distraction rate and rhythm across each osteotomy contribute to more specific information and a better understanding of the final result.

The term consolidation or maturation index (Matsubara et al. 2006) is expressed by dividing the time in the external fixator from the end of distraction with the lengthening distance. This index does not include the whole treatment period with the external device since the distraction index must be added and is therefore shorter and not accurate with respect to the complete treatment time, which is most important to the patient.

External fixation index (Tsuchiya et al. 2002) is a term which is mostly used in LON (Kim et al. 2008). In the current thesis external fixation index is identical with LI except for the LI results in Paper 3. Use of the LI term in accordance with our definition secures an accurate and comparable factor of bone healing that can be applied in general in lengthening procedures.

Complications

The Ilizarov method is associated with a high complication rate (Tjernstrom et al. 1994). Most of the clinical works published focus on reducing complications and the need for making lengthening procedures more comfortable to the patients. However, to express the complication rate, and to compare the results, there is a need for a standardized definition. To our knowledge, there is no such definition available. The most used classification system is originally published by Paley (1990).

In his original article Paley divided the complications into 3; problems, obstacles and complications:

- Problems represent difficulties that do not require operative treatment. These difficulties are expected and are fully restored by the end of the treatment period.
- Obstacles are defined as expected difficulties which occur during the lengthening or treatment period, and need operative treatment. The difficulties are fully restored at the end of the treatment.
- Complications are difficulties that include any complications associated with the procedure and which remains unresolved at the end of the treatment period. The complications are divided into minor and major. Minor complications may not lead to sequelae, but may lead to treatment delay or annoyance of the treatment.
- Major complications are divided into subgroups and represent the permanent complications including the sequelae.

Some authors refer to the 'ASAMI Group classification' of complications published in the book 'Operative Principles of Ilizarov' (Bianchi-Maiocchi and Aronson 1991). However, the chapter on complications in this book is written by Dror Paley who does not agree in the use of the term 'ASAMI Group' nomenclature or classification (personal communication, November 25, 2007). Moreover, Paley's classification has later been modified. Even if his paper from 1990 is referred to as the most frequently used classification system, Dror Paley himself in his e-mail letter declares that he later changed his original classification of 'problems, obstacles and complications' to 'problems, obstacles and sequelae' (Paley and Maar 2000). Furthermore, Paley declares: 'I then break down sequelae into resolvable major and minor and not resolvable major and minor. I also now refer to them as grade 1, 2, and 3 instead of problems, complications and sequelae'.

We prefer to simplify the definition of complications into 2 groups; minor and major:

- Minor complications are difficulties that occur during the lengthening process, but do not require hospitalisation. Joint contractures which require intensive physiotherapy to be resolved, deep pin track infection, and nerve palsy which require change of distraction rate, are examples. One operative procedure is included in the minor complication group; re-osteotomy because of premature consolidation, because it is difficult for us to consider rapid bone healing as a major complication.
- Major complications are difficulties that need hospitalisation or operative treatment such as tendon lengthening, bone grafting, removal or reinsertion of wires or pins, fractures or mali-

alignment after frame removal and infection with the need of intravenous antibiotics.

Our classification is much in coherence with Velazquez et al. and Stanitski et al. (1996). Both these papers involve complications occurring during the treatment period and also after finishing treatment, e.g malalignment, fractures etc. Aaron and Eilert (1996) classified the complications in major and minor, but with respect to the outcome of the treatment. It may be more easy to look at the result this way, because there are so many and very different kinds of problems and difficulties that occur during the treatment period. By summarising the numbers of complications in all clinical papers which refer to complications, one may end up with an average of 100% complications in every osteotomy that is performed in DO. Cherkashin (2007) stated that there is no controversy that the Ilizarov method is associated with complications, but there is no uniform approach to complications in general. He defined a complication as a deviation from the original treatment plan, which can prevent achievement of the desired outcome unless there is appropriate and timely correction. He suggests three complication categories:

- Category I: Treatment goals are achieved with minimal adjustment of the treatment plan;
- Category II: Treatment goals are achieved, but with a revision of the initial treatment plan;
- Category IIIA: Treatment goals are not achieved, but the patient condition is not worsened;
- Category IIIB: Treatment goals are not achieved, and patient condition is worse than before treatment.

In Paper 1 we compared the complications between monofocal and bifocal tibial lengthenings. We found a higher rate of major complications in the bifocal group compared to the monofocal; 16 versus 10, respectively. This is almost the same result as found by Stanitski et al. (1996). They, however, divided the complications into numbers of osteotomies on each segment and could not find a significant difference. This is coherent with our results, where the number of complications with respect to osteotomies were 8 and 10 in monofocal and bifocal lengthening, respectively.

The number of minor complications did not differ with respect to segments, but is lower in the bifocal group, if we divide complications with the number of osteotomies. The reason may be joint contractures with the need of physiotherapy, which is present in most cases of limb lengthening.

Complications associated with the LON technique are referred to as major in our Paper 3. We conclude that this method should not be used in the tibia because of the very thin soft tissue envelope and the high risk of deep IM infection. In addition slow bone formation and hardware failure were observed. These findings are not supported by other authors who strongly recommend the method. Watanabe et al. (2005) could not find any complications in 13 patients operated on with the same method, in contrary they reported fewer complications than with the traditional Ilizarov method. Lin et al. (1996) reported one deep infection at the osteotomy site and one pseudarthrosis with the need of bone grafting in 11 tibiae operated with LON. However, in contrast to our conclusion, the authors' recommendation is to use the method. Eralp et al. (2007) reported no deep infections, nail problems or reduced bone healing in combined technique and distal tibial osteotomies. They conclude that the method is an improvement over the classic external fixation techniques. Kocaoglu et al. (2004) reported 7 tibiae with 1 deep infection and 1 nonunion. In contrast to our attitude, they recommend to use the method and to be aggressive in the treatment of the complications. We have up to now not reconsidered the use of LON in the tibia, but we apply the method on the femur. We believe that the method is safer regarding deep infection on the femur because of the thick soft tissue envelope. Paley et al. (1997) reported 1 deep infection in 32 femora operated with the combined technique and in a matched comparison with traditional Ilizarov method, no difference in complication rate was found.

As the time spent in the external fixator is of the utmost importance to the patient and doctor, new and modern concepts for stimulation of bone formation have been developed both experimentally and clinically during the last recent years. These include various interventions with so far controversial results, e.g morphogenetic proteins (rhBMP) (Hu et al. 2007), growth factors (Eckardt et al. 2003), pulsed electromagnetic fields (Eyres et al. 1996), hormones (Barnes et al. 2008, Hu et al. 2007), bisphosphonates (Kiely et al. 2007), ultrasound (Shimazaki et al. 2000) and hyperbaric oxygen therapy (Wang et al. 2005). In the present work bone grafting has been used to stimulate healing in cases with delayed union and non union in DO. Recent research has revealed a potential use of skeletal muscle-derived stem cells for orthopaedic tissue engineering in regenerative medicine in orthopaedic surgery (Corsi et al. 2007). As a lot of research in these fields is going on, it is expected that some of the above mentioned experimental and clinical interventions will be used as supplemental ordinary treatment in the near future.

Conclusions

In the present work with focus on reconstructive surgery of the tibia by use of an external ring fixator and the Ilizarov method we found the following answers to the questions we asked at the initiation of the study:

1) Bifocal lengthening osteotomies by use of the Ilizarov External Fixator (IEF) result in a significant reduction of treatment and healing time compared to monofocal lengthenings evaluated by Lengthening Index (LI) in lengthenings of more than 6 cm, but more major complications like persistent ankle joint contracture and pseudarthrosis in the callotasis lengthening zone occur with bifocal lengthening.

2) No significant difference could be found between the Taylor Spatial Frame (TSF) versus IEF used in monofocal osteotomy limb lengthening and reconstructive surgery with respect to treatment and healing time evaluated by LI and complications. However, rotational, translational and residual deformity correction is easier to perform with the TSF.

3) In our hands lengthening over nail (LON) of the tibia by the combined use of an IM nail and the Ilizarov external distraction device, resulted in a high LI and unacceptable major complications.

4) By use of the high-resolution radiostereophotogrammetric analysis (RSA) method a global deformation of 15% across the zone of callotasis was found during weight bearing 6 weeks after end of distraction. This large strain value in one single case did not stimulate bone healing and delayed union was observed.

5) The Ilizarov bone transport method is useful in the treatment of Congenital Pseudarthrosis of the Tibia (CPT) to achieve primary healing, but residual challenges with secondary reconstructive surgery caused by refracture and postoperative deformities must be expected.

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