Ilizarov fixator as a method of treatment of failed internal fixation of distal tibial fractures

Mohamed A.S. Laklouk

Department of Orthopedic Surgery, Minia University, Minia, Egypt

Correspondence to Mohamed A.S. Laklouk, Department of Orthopedic Surgery, Minia University, Minia, Egypt
Tel: +00201001818256;
e-mail: m.laklok@gmail.com

Received 12 April 2011
Accepted 15 May 2011

Egyptian Orthopedic Journal 2013, 48:88–94

Background

Malunion and nonunion of the juxta-articular distal tibial fractures have been widely treated by internal fixation for many years. Over the last few decades gradual correction of the deformity and/or distraction osteogenesis with an external ring fixator have become more popular among orthopedic surgeons. Ilizarov external fixators not only correct greater degrees of deformity with lesser incidence of complications but also correct more complex deformities compared with other methods of internal fixation such as plate and screws.

Patients and methods

Between January 2006 and December 2008, 13 patients presented at the Minia University Hospital with malunion or nonunion of distal tibial fractures after failure of initial internal fixation with plates and screws. Removal of the implant, application of an Ilizarov external fixator, and adjustment of the hinges based on either the need for correction of the deformity alone or correction of the deformity and lengthening were performed. All patients were men, with an average age of 34.5 years (range, 16–52 years). The mean follow-up period was more than 24 months (range, 14–29 months). Eight patients presented with malunion and five with nonunion of the distal tibia. Three of the five patients who had nonunion presented to the department with radiological and clinical signs of osteomyelitis. One of them was treated by drainage and removal of the plate at another hospital.

Results

Osseous union was achieved in all cases. Only one patient had a residual angular deformity of less than 10°, and two patients had leg-length discrepancy of lesser than 1 cm. The mean amount of tibial lengthening measured at removal of the frame was 1.5 cm. All patients showed marked improvement in both severity and duration of pain. The mean period for which the Ilizarov external fixator was applied was 146 days (range, 87–256 days). There was no recurrence of infection in the three patients who originally presented with osteomyelitis. The functional results were categorized as excellent in four, good in seven, and fair in two patients according to the classification of the Association for the Study and Application of the Method of Ilizarov.

Conclusion

Despite the lengthy duration required for the application of the device to achieve reasonable results, gradual correction of the deformity and distraction osteogenesis can be superior alternatives for the treatment of malunion, nonunion, and/or shortening due to failure of internal fixation of distal tibial fractures.

Keywords:
distal tibial fractures, failed internal fixation, Ilizarov fixator

Egypt Orthop J 48:88–94

1110-1148

Introduction

In the treatment of fractures of the distal tibia, the goal of orthopedic management is to restore the articular alignment and regain the structural integrity of the limb. This can be accomplished with a variety of implants through well-described approaches and techniques. These traditional approaches may fail either because of technical faults or biological factors. The fixation may fail because of mechanical overload, instability, or nonunion [1]. Malunion may result in coronal, sagittal, or rotational plane deformities that are mostly likely associated with leg-length discrepancy. The development of tibial malunion and malaligned nonunion leads to alterations of the gait and the mechanics of the lower extremity. In addition, it leads to functional impairment and an unpleasant cosmetic appearance. Deviation from normal alignment leads to alterations in ankle joint reaction forces and increases shear stress on the articular cartilage, which could lead to degenerative arthritis. Surgical realignment presumably restores normal joint reaction forces and corrects the mechanical axis of the limb.

Techniques used to correct long bone malunions and malaligned nonunions include oblique, closing, or opening wedge osteotomy, dome osteotomy, corticotomy, distraction osteogenesis, and tricortical bone grafts. A wide variety of options are currently available for the fixation of an osteotomy or fracture nonunion site that has failed internal fixation. In many instances, a revision surgery using a similar or a different technique of internal fixation will lead to a successful outcome. This approach has been successful for the treatment of smaller deformities; information on the amount of angular deformity and length correction that can be achieved acutely is limited. Further, in many situations in which the overlying soft-tissue sleeve is compromised by the original injury, ensuing operative interventions can result in wound healing complications, infections, and delayed unions or nonunions. Thus, in certain cases that have failed internal fixation, the Ilizarov method may offer significant advantages. Examples of such cases include those that have failed to unite despite multiple attempts using internal fixation, those with bony fragments that are too small or too numerous for revision surgery with internal fixation (as is often seen with periarticular injuries), with an associated infection of the bone, with an associated bony defect, with osteopenic states in which bony purchase can be problematic with internal fixation, particularly screw fixation, and those with irreducible deformity at the site of nonunion. This study reviews the ability of the Ilizarov external fixation method to overcome the complications following failure of internal fixation of distal tibial fractures [2–6]. In 1979, Rosemayer defined the indications for extra-articular osteotomy as a varus deformity of greater than 6° or a valgus deformity of greater than 12°, whereas Stamatis (2004) recommended the same technique for varus or valgus deformities of greater than 10° and Kristensen (1989) reported the need for angular correction if the deformity was more than 15°. A varus deformity of the distal tibia is less tolerated than a valgus deformity because of a greater compensatory inversion at the subtalar joint. Treatment of such deformities must be early (within a year), and ideally before the onset of articular degeneration [7–9].

Patients and methods

Between January 2006 and January 2008, 13 patients with malunion or nonunion of extra-articular distal tibial fractures due to failed open reduction and internal fixation using plates and screws presented at the Orthopedic Department of the Minia University Hospital. All of them were treated with an Ilizarov external fixator and distraction osteogenesis if required. The inclusion criteria for this study were (a) failure of internal fixation of a distal tibial fracture that was initially managed by the plate and screw technique, resulting in malunion or nonunion of the distal tibia and (b) a deformity in the distal third of tibia. Malunion was defined according to the description by Borrelli *et al.* [10], who described deformities in the coronal plane as those with more than 5° varus or 10° valgus angulation and deformities in the sagittal plane as those with more than 15° procurvatum or recurvatum. According to Wyrsch [11], nonunion was diagnosed if the fracture failed to show clinical and radiographic union after 6 months from the initial injury. The possibility of local infection was addressed by assessing for clinical signs and raised inflammatory markers (sedimentation rate, C-reactive protein, and white blood cell count). Exclusion criteria were (a) severe ankle arthropathy, (b) higher diaphyseal level of the deformity, (c) current or previous deformity in the contralateral tibia, (d) previous surgical management other than removal of plates or debridement for infection, and (e) severely osteoporotic bone. All patients were followed up for at least 2 years. Patients demographic data are listed in Table 1. All patients were men. The average age at presentation was 34.5 years (range, 16–52 years). Five patients had nonunion of the distal tibia (three of them showed infected nonunion). Eight patients presented with malunion: five of them had a valgus deformity with an average angulation of 21.4° (range, 18–30°), two patients showed a pure varus deformity with a mean angulation of 18.5° (range, 15–22°), and one patient showed an oblique plane deformity with procurvatum 29° and varus 12° (Fig. 1). The implant was removed from all patients except one in whom the plate was removed before application of the fixator. Appropriate antibiotics were administered to

Table 1 Demographic data, postoperative complications, and functional and bony results of the patient group

	Age(years)	Etiology	Deformity	Infection	Shortening (cm)	Procedure	Complications	ASAMI Bony	ASAMI Functional
1	35	Nonunion	–	–	2	S L	–	E	G
2	32	Malunion	15° VR	–	–	S C	–	E	E
3	16	Malunion	19° VL	–	–	S C	–	E	E
4	28	Nonunion	–	Septic	2	S L	Supr. Inf.	E	G
5	40	Malunion	29° Pr, 12° VR	–	–	S C	–	E	G
6	43	Nonunion	–	Septic	1.5	S L	–	E	G
7	50	Malunion	22° VR	–	1	S C L	–	E	G
8	25	Malunion	18° VL	–	–	S C	–	E	E
9	36	Nonunion	–	Septic	3	S L	Supr. Inf.	G	F
10	45	Malunion	30° VL	–	–	S C	–	E	G
11	48	Malunion	20° VL	–	–	S	Shift of MA	E	G
12	52	Nonunion	–	–	–	S C	–	E	E
13	18	Malunion	20° VL	–	3	S C L	Delayed union	P	F

C, correction; E, excellent; F, fair; G, good; L, lengthening; MA, mechanical axis; P, poor; Pr, procurvatum; S, stabilization; Supr. Inf., superficial infection; VL, valgus; VR, varus.

Figure 1

(a) Radiograph of a 40-year-old man showing failed internal fixation, malunion in form of 32° procurvatum and 12° varus, and a broken plate. (b) Photograph of the patient (c) after removal of the plate and application of the Ilizarov fixator, showing good correction, and (d) at the end of follow-up, showing healing of the fracture but with about 7° valgus.

patients with infected nonunion according to the culture and sensitivity test. However, if the causative organism could not be identified, broad-spectrum antibiotics were administered.

Preoperatively and during the postoperative follow-up period, bilateral full-length weight bearing radiographs of the tibia including the knee and the ankle joint were obtained for all patients. On the anteroposterior view we recorded the tibial–ankle surface (TAS) angle formed between two lines: one representing the mechanical axis of the tibia and the other completely parallel to the distal tibial articular surface. We used the same lines to measure the tibial lateral surface (TLS) angle on the lateral view. The average normal values for the TAS and TLS angles were 93 and 80°, respectively [12]. We preferred to measure these angles using the contralateral sound limb to avoid any bias in our results based on individual variations. The aim of the present study was normalize the values of TAS and TLS angles in patients with malunion, perhaps adding 5–10° for slight overcorrection to account for any subsidence that could occur after osteotomy. The full-length weight bearing radiographs were also used to measure the preoperative leg-length discrepancy.

Meticulous preoperative planning was performed in all patients to accurately identify the level and degree of deformity, the degree of displacement of the mechanical axes, the amount of correction required, and the sequence of intraoperative steps for Ilizarov application. Sedimentation rate, C-reactive protein levels, and white blood cell count were determined at the baseline and during follow-up. The choice of anesthesia was completely dependent upon patient safety and the anesthetist's preference.

Operative technique

For correction of distal deformities of the lower limb, the assembly extends from the proximal part of the tibia to the foot if the quality of the bone requires this; the frame was applied as follows: insertion of two wires, one of which is transfibular, and one or two half pins and fixation of them onto a ring; insertion of two wires and one half pin into the middle third and fixation onto a ring; insertion of three distal wires, one of which is transfibular, and fixation onto a ring. The fixator is placed as close to the unstable area as possible both proximally and distally. For each segment, the fixator should extend as far as possible away from the area being treated. For the proximal segment, the frame should extend to the proximal metaphyseal diaphyseal junction. The assembly is completed with threaded rods; the correction system made of two universal hinges is applied according to the axis of rotation on the upper surface of the third ring, and two motors for gradual correction of the deformity are fitted. The level of the hinge relative to the osteotomy will determine the type of correction. A hinge on the bisector line over the convex cortex with osteotomy passing through the CORA leads to opening wedge correction with complete realignment. A hinge on the bisector line but more convex than the convex cortex and osteotomy at the level of the CORA lead to angular correction without translation of the axis line or bone ends but with lengthening separation of the bone ends; this technique is suitable for correction of angular deformity and shortening. A hinge proximal to the CORA and osteotomy at the CORA leads to translation of the bone ends and the axis lines. A hinge at the level of CORA with osteotomy distal to the CORA leads to translation of the bone ends but not of the axis lines. If the area of failure is so distal enough that even 2–3 cm of quality bone is not available for fixation, the frame should cross the ankle to include the foot and be fixed with a half-ring at the calcaneus level, with two correction rods and one half-ring for the stabilization of the forefoot, to prevent equinus deformity of the foot. The actual reduction of the malalignment can be performed with slow distraction. In the presence of infection or large nonunion, there is frequently a bone defect created by the debridement of infected or nonviable tissue. The frame can be designed to allow for either distal or proximal distraction osteogenesis at a later time to restore length once the alignment is stable.

Postoperative radiological and clinical follow-up were performed at weekly intervals in the outpatient clinic until correction of the deformity, thereafter every 15 days until fracture union was achieved. The average duration of follow-up was 24 months (range, 14–29 months). Preoperative limb shortening was recorded in six patients, averaging 2.1 cm (range, 1–3 cm).

Results

The classification system of the Association for the Study and Application of the Method of Ilizarov [13] was used during the follow-up period to interpret the results of the present study. This classification system is based on two categories: bone and functional outcomes. Bone outcome depends upon four criteria: union (when at least three cortices can be seen in both anteroposterior and lateral view radiographs), infection, deformity, and leg-length discrepancy. Functional evaluation included five criteria: presence of a limp, stiffness of the ankle, pain, soft-tissue sympathetic dysfunction, and the ability to perform previous activities of daily living. Our patients were assigned four grades on the basis of the described criteria: excellent, good, fair, and poor. A bone result was considered excellent when there was union, no infection, deformity of less than 7°, and leg-length discrepancy of less than 2.5 cm in the tibia. Union along with any two of the four criteria was rated as a good result, whereas union along with one other criterion was interpreted as a fair result. Finally, the result was considered to be poor in the case of nonunion or refracture and when none of the criteria were fulfilled. Active individuals who did not fulfill any of thefour criteria were considered to show excellent functional results; those fulfilling one or two of the other four criteria were considered to show good results; and those fulfilling three or four of the other criteria or who had undergone an amputation were considered to show fair results. An inactive individual was considered to show a poor result regardless of the other criteria. Postoperatively, limb-length inequality was corrected in all patients except one patient who had a leg-length discrepancy of 1 cm.

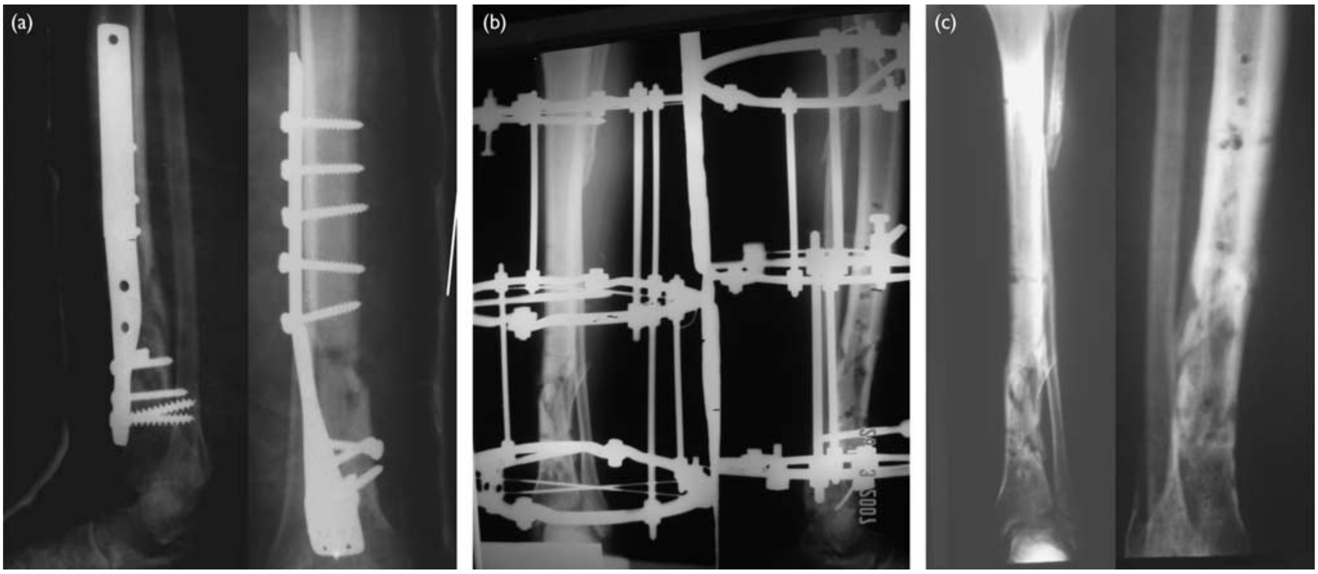
At the end of follow-up period, all patients reported improvement in the frequency and severity of pain. At the final clinical follow-up, four patients showed full and symmetrical range of ankle joint motion comparable to the preinjury range of motion (ROM). Six patients had limited ROM, which had improved compared with their preoperative ROM. Unfortunately, the remaining three patients showed no change in ROM. All feet were found to be plantigrade immediately after removal of the external fixators. On the basis of these data, functional results were categorized as excellent in four, good in seven, and fair in two patients.

Osseous union was achieved in all patients except one belonging to the nonunion group who had original shortening; an iliac bone marrow injection was administered in this case to ensure healing (Fig. 2). Preoperative angular deformity was fully corrected in all patients except one who had a residual valgus angular deformity of less than 10°. The mean amount of lengthening performed using the Ilizarov technique was 2.1 cm (range, 1–3 cm). The mean period required for external fixation was 146 days (range, 87–256 days). During follow-up, there were no manifestations of recurrence of infection in the three patients with preoperative history of septic nonunion. According to the evaluation system, bone results were found to be excellent in 12 patients and poor in one.

Complications

One patient had delayed union of the osteotomy and required alternating axial compression and distraction in addition to bone marrow injection. Superficial wound infection in two patients has been addressed and managed by local wound care and administration of

Figure 2



(a) Radiograph of a 52-year-old man showing failed internal fixation, nonunion, and a broken plate (b) after removal of the plate and application of an Ilizarov fixator and (c) at the end of follow-up, showing healing of the fracture.

appropriate antibiotics. One patient showed a shift in the mechanical axis to the medial aspect of the ankle joint and was treated by bone translation through a slight modification of the frame and correction of this iatrogenic deformity (Fig. 3).

Discussion

Nonunion of juxta-articular fractures is uncommon because of the efficient vascularity of this area and the large cross-sectional area of the trabecular bone [14–16]. However, when there is considerable periosteal stripping, soft-tissue necrosis, or bone loss affecting such a metaphyseal area, nonunion may result. This may happen when infection complicates internal fixation or in the case of a high-energy injury trauma [17]. Failure of fixation or fracture nonunion following internal fixation can be defined in many ways. This can be related to the mechanical construct, the local biology at the site of injury, or both. Mechanical instability following internal fixation results in excessive motion at the site of the bone injury, impairing the fracture repair process. This instability often results from and can further potentiate hardware loosening and fatigue failure, which in turn lead to further instability. Biological failure can result from inadequate vascularity, poor bone-to-bone contact, or both. Healing may be adversely affected by the severity of the injury, suboptimal surgical fixation either due to a poor treatment plan or a good plan carried out poorly, or a combination of both. In many instances, a revision surgery using a similar or a different type of internal fixation will lead to a successful outcome. In certain patients with failure of internal fixation, such as those with failure of union despite multiple attempts using internal fixation, with fractures in which bony fragments are too small or too numerous for revision surgery with internal fixation, as is often seen with periarticular injuries, with associated bone infection and bony defects, severely osteopenic bones in which bony purchase can be problematic with internal fixation, particularly screw fixation, and those with severe deformity at the site of nonunion, the Ilizarov method may offer significant advantages. Moreover, Ilizarov external fixation has the advantage of percutaneous application, being minimally invasive without the requirement for any aggressive soft-tissue dissection, allowing immediate weight bearing and early joint mobilization, and being versatile. It can promote generation of bony tissue. Thus, it is efficient in simultaneous bony healing and deformity correction [18–20].

Treatment by the Ilizarov method can be adjusted from time to time through frame modification when a fracture or fracture nonunion fails to show progression to healing. Generally, frame modification is not painful, does not require anesthesia, and can be performed at an outpatient clinic. By contrast, modification of plate and screw fixation requires repeated surgical intervention. A variety of treatment modalities can be adopted using the Ilizarov method. These include compression, distraction, lengthening, bone transport, and deformity correction. The technique of frame application may be monofocal or bifocal. The use of the Ilizarov method to treat a periarticular fracture or nonunion with small bony fragments following failed internal fixation may require spanning of the ankle joint to achieve adequate stability. Once radiographic evidence for progression to bone healing is obtained, the fixator can be modified so that it no longer spans the ankle joint. This would help the patient perform ROM exercises to prevent contractures and preserve muscle function. Stiffness or deformity of the ankle joint adjacent to the fracture site can adversely affect the outcome if it is not addressed [19].

Figure 3

(a) Radiograph of a 48-year-old man showing malunion of the tibia. (b) Photograph of the patient in the standing position shows valgus deformity of the ankle. (c) Radiograph showing correction of the valgus deformity; however, there is a lateral shift in the mechanical axis (MA). (d) Radiograph showing correction of the translation of MA by modifying the frame. (e) Radiograph after removal of the Ilizarov fixator, with healing of the osteotomy and correction of the translation deformity. (f) Photograph of the patient in a standing position showing that the deformity is corrected during application of the Ilizarov fixator.

Infection of a fracture or fracture nonunion following failed internal fixation is challenged by two of the most difficult orthopedic entities to treat: bone infection and fracture nonunion. These two hassles following failed internal fixation are often accompanied by incapacitating pain (with narcotic dependency), soft-tissue problems, deformities, joint problems, motor and sensory dysfunction, osteopenia, poor general health, depression, and a myriad of other problems. The goals in treating these problems are to obtain solid bony union, to eradicate the infection, and to maximize function of the extremity and improve patient's lifestyle. With appropriate planning and close follow-up, this technique allows safe and predictable correction of complex multiplanar deformities in patients with limb-length inequalities. Nonunion and malunions near the joint may be complicated by overlying soft tissues problems due to preceding injuries or operative interventions. Therefore, it is desirable to keep local incisions and dissections to a minimum [21–27].

The results of the present study were compared with those of published studies on different methods of treatment of malunions and malaligned nonunions of the tibia and fibula after fracture. Borrelli *et al.* [10] in their work used tricortical bone grafts for the treatment of malaligned tibias and fibulas; they found that 16 patients (94%) showed clinical and radiographic evidence of healing at the operative site at an average of 99 days (range, 43–229 days) postoperatively, and only one patient had a persistent nonunion (6%). They also reported other complications such as a secondary flap for wound dehiscence in one patient, need for irrigation and debridement plus intravenous antibiotics for wound infection in one patient, removal of the distal fibula after development of arthritis at the fibulotalar joint in one patient, a persistent accepted ankle deformity that did not require surgical correction in one patient, and finally, moderate discomfort at the graft site 3 months postoperatively, which resolved by the time of the final follow-up, in one patient. In the present study, it was found that osseous union was achieved in all patients except one belonging to the nonunion group; repeated attacks of compression and distraction, followed by iliac bone marrow injection was applied in this case to ensure healing. One patient showed a shift in the mechanical axis to the lateral aspect of the ankle joint and was treated by bone translation through slight modification of the frame and correction of this iatrogenic deformity. Superficial wound infection was reported in two patients and was addressed and managed by local wound care and administration of the appropriate antibiotic.

We compared the results of this study with those of studies that used the same method of treatment for malunions and malaligned nonunions of the tibia and fibula after fracture. Tetsworth and Paley [4] in their study found that the average duration for external fixation was 158 days. However, in our series the mean period required for external fixation was 146 days (range, 87–256 days). Motsitsi [27] conducted a study on infected pseudoarthrosis following plate fixation of the distal tibia. He treated this case with debridement, mesh cage, autologous grafting, and locking plate fixation. He obtained a satisfactory outcome despite residual limb deformity and discrepancy. In the study by Kabata *et al.* [17] on seven juxta-articular nonunions (five septic and two aseptic), the location of the nonunion was the distal femur in four patients, the proximal tibia in one patient, and the distal tibia in two patients. The reconstructive procedure consisted of refreshment of the nonunion site, deformity correction, stabilization by external fixation, and lengthening to eliminate leg-length discrepancy or to fill the defect. Osseous union without angular deformity more than 10° or leg-length discrepancy greater than 1 cm was achieved in all patients. The mean amount of lengthening was 5.8 cm (range, 2.2–10.0 cm). The mean external fixation period was 219 days (range, 98–317 days). All patients reported excellent pain reduction. There were no recurrences of infection in the five patients with a history of osteomyelitis. The functional results were categorized as excellent in two, good in three, and fair in two patients. These results were comparable to our results.

There are a few limitations to the present study, such as the decreased sample size, which reduces the ability to detect the possible real differences that might exist between all techniques.

Conclusion

There are many reasons for failure of internal fixation of distal tibial fractures treated using plates. Revision of internal fixation using the same or a different internal fixation technique may be successful. However, in certain cases the Ilizarov method may be the preferred treatment strategy following failed internal fixation, especially in the case of small or numerous bony fragments, bone infection, bony defects, and/or osteopenia. The Ilizarov method offers many advantages for the treatment of fracture or fracture nonunion following failed internal fixation. We recommend the Ilizarov method as a valuable alternative for the treatment of malunion, nonunion, and/or shortening due to failure of internal fixation of distal tibial fractures.

Acknowledgements

Conflicts of interest

There are no conflicts of interest.

References

1 Cheleuitte D, Early J. Failed internal fixation about the distal tibia. Tech Orthop 2003; 17:479–489.

2 Graehl PM, Hersh MR, Heckman JD. Supramalleolar osteotomy for the treatment of symptomatic tibial mal-union. J Orthop Trauma 1987; 1:281–292.

3 Tarr RR, Resnick CT, Wagner KS, Sarmiento A. Changes in tibiotalar joint contact areas following experimentally induced tibial angular deformities. Clin Orthop Relat Res 1985; 199:72–80.

4 Tetsworth K, Paley D. Malalignment and degenerative arthropathy. Orthop Clin North Am 1994; 25:367–377.

5 Yablon IG. Treatment of ankle malunion. Instr Course Lect 1984; 33: 118–123.

6 Johnson EE. Acute lengthening of shortened lower extremities after malunion or nonunion of a fracture. J Bone Joint Surg 1994; 76A:379–389.

7 Kristensen KD, Kiaer T, Blicher J. No arthrosis of the ankle 20 years after malaligned tibial-shaft fracture. Acta Orthop Scand 1989; 60:208–209.

8 Stamatis E, Myerson M. Supramalleolar osteotomy for the treatment of distal tibial angular deformities and arthritis of the ankle joint. Tech Foot Ankle Surg 2004; 3:138–142.

9 Lindvall E, Sanders R. Supramalleolar osteotomies and angular corrections. Techn Foot Ankle Surg 2005; 4:70–78.

10 Borrelli J, Leduc S, Gregush R, Ricci W. Tricortical bone grafts for treatment of malaligned tibias and fibulas. Clin Orthop Relat Res 2009; 467: 1056–1063.

11 Wyrsch B, Mcferran M, McAndrew M, Limbird T, Harper M, Johnson K, Schwartz H. Operative treatment of fractures of the tibial plafond. A randomized, prospective study. J Bone Joint Surg Am 1996; 78:1646–1657.

12 Geert I, Hintermann B, Barg A, Leumann A, Valderrabano V. Realignment surgery as alternative treatment of varus and valgus ankle osteoarthritis. Clin Orthop 2007; 462:156–168.

13 Emara K, Allam M. Ilizarov external fixation and then nailing in management of infected nonunions of the tibial shaft. J Trauma 2008; 65:685–691.

14 Mandt PR, Gershuni DH. Treatment of nonunion of fractures in the epiphyseal–metaphyseal region of long bones. J Orthop Trauma 1987; 1:141–151.

15 McKibbin B. The biology of fracture healing in long bones. J Bone Joint Surg Br 1978; 60:150–162.

16 Rhinelander FW. Tibial blood supply in relation to fracture healing. Clin Orthop 1974; 105:34–81.

17 Kabata T, Tsuchiya H, Sakurakichi K, Yamashiro T, Watanabe K, Tomita K. Reconstruction with distraction osteogenesis for juxta-articular nonunions with bone loss. J Trauma 2005; 58:1213–1222.

18 Brinker M, O'Connor D. The use of Ilizarov external fixation following failed internal fixation. Tech Orthop 2002; 17:490–505.

19 Brinker MR, Bailey DE. Fracture healing in tibia fractures with an associated vascular injury. J Trauma 1997; 42:11–19.

20 Chatziyiannakis AA, Verettas DA, Raptis VK, Charpantitis ST. Nonunion of tibial fractures treated with external fixation. Contributing factors studied in 71 fractures. Acta Orthop Scand Suppl 1997; 275:77–79.

21 Behrens F, Sabharwal S. Deformity correction and reconstructive procedures using percutaneous techniques. Clin Orthop Relat Res 2000; 375:133–139.

22 Moreland JR, Bassett LW, Hanker GJ. Radiographic analysis of the axial alignment of the lower extremity. J Bone Joint Surg 1987; 69A:745–749.

23 Paley D, Herzenberg J, Tetsworth K, McKie J, Bhave A. Deformity planning for frontal and sagittal plane corrective osteotomies. Orthop Clin North Am 1994; 25:425–465.

24 Paley D, Tetsworth K. Mechanical axis deviation of the lower limbs: preoperative planning of multiapical frontal plane angular deformities of the femur and tibia. Clin Orthop 1992; 280:65–71.

25 Puno RM, Vaughan JJ, von Fraunhofer JA, Stetten ML, Johnson JR. A method of determining the angular malalignments of the knee and ankle joints resulting from a tibial malunion. Clin Orthop 1987; 223:213–219.

26 Puno RM, Vaughan JJ, Stetten ML, Johnson JR. Long-term effects of tibial angular malunion on the knee and ankle joints. J Orthop Trauma 1991; 5:247–254.

27 Motsitsi S. Methicillin-resistant *Staphylococcus aureus* infected pseudo-arthrosis of the distal tibia treated with debridement, mesh cage, autologous grafting and locking plate fixation. Strategies Trauma Limb Reconstr 2008; 3:97–99.