Repair of Tibial Nonunions and Bone Defects with the Taylor Spatial Frame

S. Robert Rozbruch, MD, Jacob S. Pugsley, MD, Austin T. Fragomen, MD, and Svetlana Ilizarov, MD

Objective: To investigate the outcomes of tibial nonunions and bone defects treated with the Taylor Spatial Frame (TSF) using the Ilizarov method.

Design: Retrospective.

Setting: Limb Lengthening and Deformity Service at an academic medical center.

Patients: Thirty-eight consecutive patients with 38 tibial nonunions were treated with the TSF. There were 23 patients with bone defects (average 5.9 cm) and 22 patients with leg-length discrepancy (LLD) (average 3.1 cm) resulting in an average longitudinal deficiency (sum of bone defect and LLD) of 6.5 cm in 31 patients (1–16). The average number of previous surgeries was 4 (0–20). At the time of surgery, 19 (50%) nonunions were diagnosed as infected.

Intervention: All patients underwent repair of the nonunion and application of a TSF. Patients with bone loss were additionally treated with lengthening. Infected nonunions were treated with 6 weeks of culture-specific antibiotics.

Main Outcome Measurements: Bony union, time in frame, eradication of infection, leg-length discrepancy, deformity, Short Form-36 (SF-36) scores, American Academy of Orthopaedic Surgeons (AAOS) lower-limb scores, and Association for the Study of the Method of Ilizarov (ASAMI) bone and functional results.

Results: Bony union was achieved after the initial treatment in 27 (71%) patients. The presence of bone infection correlated with initial failure and persistent nonunion ($P = 0.03$). The 11 persistent nonunions were re-treated with TSF reapplication in 4, intramedullary rodding in 3, plate fixation in 2, and amputation in 2 patients. This resulted in final bony union in 36 (95%) patients. The average LLD was 1.8 cm (0–6.8) (SD 2). Alignment with deformity less than 5° was achieved in 32 patients and alignment between 6° and 10° was achieved in 4 patients. Significant improvement of Short Form-36 (SF-36) scores was noted in physical role ($P = 0.03$) and physical function ($P = 0.001$). AAOS lower-limb module scores significantly improved from 56 to 82 ($P < 0.001$). ASAMI bone and functional outcomes were excellent or good in 36 and 34 patients, respectively. The number of previous surgeries correlated inversely with the ASAMI bone ($P = 0.003$) and functional ($P = 0.001$) scores.

Conclusions: One can comprehensively approach tibial nonunions with the TSF. This is particularly useful in the setting of stiff hypertrophic nonunion, infection, bone loss, LLD, and poor soft-tissue envelope. Infected nonunions have a higher risk of failure than noninfected cases. Treatment after fewer failed surgeries will lead to a better outcome. Internal fixation can be used to salvage initial failures.

Key Words: Taylor Spatial Frame (TSF), Ilizarov method, tibial nonunions, bone defects

(*J Orthop Trauma* 2008;22:88–95)

INTRODUCTION

Tibial nonunions have been treated with a variety of surgical methods including plate osteosynthesis with bone graft,[1–3] intramedullary nailing,[4–7] and external fixation.[8–16] The complexity of a tibial nonunion can be variable and depends on several factors. The "personality of a fracture" is a term and concept introduced by Schatzker[17] and its use underscores the complexity of a particular problem and helps organize a treatment approach. We have found it helpful to apply this concept to nonunion. The personality of a tibial nonunion is determined by a number of factors including bone loss; radiographic appearance and stiffness as they relate to the nonunion biology; deformity; leg-length discrepancy (LLD); presence or history of infection; soft-tissue envelope; retained hardware; and patient factors including diabetes, smoking, and neuropathy. Although the use of internal fixation is effective in the treatment of selected tibial nonunions, these techniques have their limitations.

The Ilizarov method has gained many advocates for the treatment of tibial nonunions over the last 2 decades, particularly hypertrophic nonunions[8,12,13,15,16,18,19] and nonunions associated with bone loss,[9,12,20–23] infection,[9,24,25] and a poor soft-tissue envelope.[12,20,26] The classic Ilizarov frame has been used to correct all deformity,[10,18,27–30] including lengthening and bone transport.[20,22,26] However, deformity correction with components of angulation, translation, and rotation requires a staged correction and frame modifications.

The TSF (Smith and Nephew, Inc., Memphis, Tennessee) is an evolution of the original Ilizarov frame and uses the same concepts of distraction osteogenesis as the classic frame. However, it uses a virtual hinge and a computer program to

Accepted for publication November 19, 2007.
From the Institute for Limb Lengthening and Reconstruction Limb Lengthening and Deformity Service, Hospital for Special Surgery, Weill Medical College of Cornell University, New York, New York.
Reprints: S. Robert Rozbruch, MD, 535 East 70th Street, New York, New York 10021 (e-mail: Rozbruchsr@hss.edu).

simultaneously correct length and all aspects of deformity including angulation, translation, and rotation.[10,15,31]

We have used the TSF and the Ilizarov method to comprehensively approach these complicated and in many cases limb-salvage situations. The purpose of this study was to review the results of our experience with a consecutive series of complex tibial nonunions and bone defects. Although our initial intention was not to use internal fixation, we did use it to successfully salvage some initial failures.

PATIENTS AND METHODS

After obtaining Institutional Review Board approval, our registry was used to identify the study population. Between 1999 and 2003, 38 consecutive patients with 38 tibial nonunions were treated with the TSF. There were 30 men and 8 women with an average age of 43 years (8–72). Our study population contained a wide range of conditions, which made this a challenging group of patients. There were 10 patients who smoked and 4 people with diabetes including 1 who was status post-kidney transplant with blindness and neuropathy, 1 with psoriasis, and 1 with asthma and hypertension. One patient had rheumatoid arthritis. One patient had 15 degrees of equinus contracture of the ankle. One patient had prostate cancer. One patient was addicted to heroin and crack cocaine. Five patients had asthma (including the patient with diabetes described earlier), including 1 with emphysema. One patient had hemochromatosis and testicular cancer.

The nonunions were the outcome of closed fractures in 10, open fractures in 26, bone defect following failed tumor reconstruction in 1, and osteomyelitis and bone defect following a snake bite in 1 patient. Ten patients had previous flaps and 17 patients presented with drainage. There were 18 atrophic, 14 normotrophic, and 6 hypertrophic nonunions. The tibial location of the nonunion was proximal in 6, middle in 12, and distal in 20. There were 23 patients with bone defects with an average size of 5.9 cm (1.5–16). LLD was present in 22 patients with an average of 3.1 cm (1–5.7). This resulted in an average longitudinal deficiency (sum of bone defect and LLD) of 6.5 cm in 31 patients (1–16).

There was a history of infection in 23 patients treated previously with antibiotics. At the time of surgery, 19 (50%) nonunions were diagnosed as infected, and these patients were treated with 6 weeks of culture-specific antibiotics. Organisms cultured at the time of surgery included *Pseudomonas aeruginosa, Staphylococcus epidermidis, Staphylococcus aureus, methicillin-resistant Staphylococcus aureus (MRSA), Enterococcus faecalis, Citrobacter freundii, Serratia marcescens, Streptococcus viridans,* group B streptococcus, and *Staphylococcus maltophia*. Four patients grew multiple organisms.

The average number of previous surgeries was 4 (0–20). Nine patients were previously treated with plates. Ten patients were previously treated with rods. Nineteen patients were previously treated with external fixation. Five patients were previously treated with bone grafts. Ten patients were previously treated with flaps. Fifteen of the patients in our study had been unsuccessfully treated with 2 or more of these modalities. During our treatment, 2 patients underwent free flaps and 2 patients underwent simultaneous bone and soft-tissue transport.

Bone grafting with demineralized bone matrix (DBM) was performed in 25 (66%) patients. Distraction osteogenesis for bone transport or lengthening was performed in 20 (53%) patients with an average of 6.7-cm length (2.5–16) (SD 3.3). This was achieved at the proximal tibia in 13, distal tibia in 2, both locations (trifocal technique) in 3, and femur in 2. To enhance bone healing, external electrical stimulation was used in 22 patients, internal electrical stimulation was used in 1 patient, and ultrasound was used in 8 patients.

Clinical follow-up was obtained consisting of physical examination, radiographs, SF-36 scores, AAOS lower limb module scores, and ASAMI classification of results (which scores a separate bone and functional outcome).[22,23]

The outcomes of different subgroups and variables were evaluated for differences. These included infection, size of bone defect, nonunion location, nonunion type, and previous treatment.

Our approach to the nonunions was based on presence of infection, nonunion type, soft-tissue situation, bone loss, and LLD. All nonunions were treated with the TSF and Ilizarov method. However, different strategies were used, including acute or gradual correction, open or closed approach to the nonunion, simultaneous or staged lengthening, insertion of antibiotic beads, application of flap, or soft-tissue transport. This is further elaborated in the Discussion section.

Initial bony union failures were re-treated with use of internal fixation, external fixation, or amputation based on the individual situation.

STATISTICAL METHODS

Because this study has a small sample and multiple comparisons, unadjusted P values have been quoted. Statistical analysis was performed using the Fisher's exact test, Pearson's correlation, Spearman's rank correlation, Mann-Whitney test, paired Wilcoxen test, and paired t-tests as was felt to be most appropriate by the statistician.

RESULTS

The average follow-up after frame removal was 37 months (15–63; SD 13). The frame was used dynamically in distraction and/or compression for a duration of 132 days (15–480; SD 161). The total time in the frame averaged 289 days (119–715). The presence of preoperative bone infection correlated with increased time in the frame ($P = 0.02$, Mann-Whitney test). The subgroup without bone infection wore the frame for a mean of 216 days (SD 102), and the subgroup with bone infection wore the frame for a mean of 344 days (SD 172). The size of bone defect correlated with longer time in frame ($P < 0.001$, Pearson's correlation).

Bony union was achieved after the initial treatment in 27/38 (71%) patients. Nine of these 11 initial failures were in the infected nonunion group. The presence of bone infection correlated with initial failure and persistent nonunion ($P = 0.03$, Fisher's exact test). We did not find any correlation between outcome of nonunion and associated conditions of diabetes or smoking. No correlations between bony union and previous treatment, nonunion location, nonunion type, presence or size of bone defect, and specific organism of infection were found.

The 11 persistent nonunions were re-treated with TSF reapplication in 4, intramedullary rodding in 3, plate fixation in 2, and amputation in 2 patients. This resulted in final bony union and absence of infection in 36/38 (95%) patients. Two patients with persistent nonunion and infection were treated with amputation. One patient was treated with a transtibial amputation, and 1 patient with a very proximal infected tibial nonunion was treated with a transfemoral amputation. The average final LLD was 1.8 cm (0–6.8; SD 2). Alignment with deformity less than 5° was achieved in 32 patients and between 6° and 10° was achieved in 4 patients.

SF-36 scores improved in 6 of 8 categories including physical role, physical function, general health vitality, social function, and mental health. Significant improvement was noted in 2 categories of the SF-36. Physical function improved from a mean of 19 to 51 (P = 0.001), and physical role improved from a mean of 21 to 51 (P = 0.03) (paired Wilcoxen test). Mean AAOS lower limb module scores significantly improved from 56 to 82 ($P < 0.001$) (paired Wilcoxen test).

According to the ASAMI classification of results, there were 24 excellent, 12 good, and 2 poor bone outcomes and 20 excellent, 14 good, 2 fair, and 2 poor functional outcomes. The number of surgeries performed prior to our treatment correlated inversely with the ASAMI bone (P = 0.003) and functional scores (P = 0.001; Spearman's rank correlation).

DISCUSSION

Although bone grafting or noninvasive stimulation[32,33] can be effective in certain situations, these modalities used exclusively do not address instability or deformity at the nonunion. Whereas the use of plates[1–3,21,34] and intramedullary nails[4–7,21,35] are effective in the treatment of selected tibial nonunions, these techniques have their limitations. Their use requires acute correction, so large deformity cannot be addressed safely. Additionally, bone lengthening or transport for LLD and bony defects cannot be performed with these tools. Of 33 tibia fractures previously treated with reamed intramedullary nailing studied by Court-Brown et al[4] that did not unite, exchange to another reamed nail provided good results, with the exception of fractures with significant bone loss (50% cortical diameter of tibia spanning 1 cm or more). Also, in the setting of infection, or previous treatment with external fixation,[35] or a poor soft-tissue envelope, internal fixation may be less desirable.

Gradual correction with a specialized frame is useful for large deformity correction, associated limb lengthening, bone transport to treat segmental defects,[9,12,20,22,23,26,36,37]and stiff hypertrophic nonunion repair.[8,10,12,13,15,16] Gradual correction uses the principle of distraction osteogenesis.[12,18] Bone and soft tissue is gradually distracted at a rate of approximately 1 mm per day in divided increments. In the present series of nonunions with deformity and bone loss, the TSF was used dynamically in distraction and/or compression for a duration of 132 days (15–480). Dynamic use of the TSF included correction of deformity, bone transport for bone defects, and gradual compression of the nonunion.

Deformity corrections were performed either acutely or gradually with the TSF. Acute corrections were reserved for modest deformities. Acute correction of large deformity was avoided because of a concern regarding stretch injury to the neurovascular structures and skin.[10,15,31] We used the TSF to correct primary deformities such as in stiff nonunions and secondary deformities that occurred during lengthening and bone transport.

Consideration of the biology of the nonunion helped us plan our treatment. There were 6 stiff nonunions (noted after osteotomy of the fibula) in the current series. These were noted to be hypertrophic nonunions on x-ray. Ilizarov[8,12] introduced the approach for treating stiff hypertrophic nonunions using an external fixator to stimulate osteogenesis by distraction of the fibrocartilage at the nonunion site. Gradual distraction to achieve normal alignment results in bone formation. Several studies have confirmed Ilizarov's success with this technique.[8,13,15,16,19] The principal advantages are not having to open the nonunion site in the face of poor skin and widened callus and gaining length through an opening wedge correction (Fig. 1).

Eighteen atrophic nonunions were mobile after fibula osteotomy in the current series. Treatment was directed toward improving both the biology and the mechanical environment to achieve bony union. The 14 normotrophic nonunions were noted to be somewhere between atrophic and hypertrophic in terms of stability and radiographic appearance. Atrophic and some normotrophic nonunions were exposed, fibrous tissue was removed, bone ends were contoured so there was healthy bleeding bone on both sides with good contact, and intramedullary canals were opened. Stripping of soft tissue was kept to a minimum. Acute correction of deformity was followed by bone grafting and stable fixation with compression.

A helpful feature of the TSF was that in addition to the ability to acutely compress the nonunion in surgery, we could add more compression during the postoperative period even when the rings were not parallel. Partial correction of the deformity could also be done with the remainder of the correction performed gradually if the soft-tissue situation mandated this.

Some of the normotrophic nonunions in the current series were alternatively approached with the use of gradual correction. The nonunion was approached in a minimally invasive fashion through 1–2 cm incisions. With the aid of intraoperative fluoroscopy, the nonunion was mobilized with an osteotome and the intramedullary canals were opened by using a cannulated drill and curettes. Bone graft then was inserted through a small diameter tube. The frame was then applied and used to gradually correct the deformity and achieve optimal bone contact. Once this was accomplished, axial compression was performed. Full weightbearing was allowed immediately after surgery. If additional length was needed, an osteotomy for gradual lengthening was performed at a different site.

For the infected nonunions, the patients had been off all antibiotics for several weeks and multiple intraoperative cultures and pathology specimens were sent to the laboratory at the time of surgery. Seventeen of our patients presented with drainage. There were 19 (50%) in the current series with positive intraoperative cultures. Infected nonunions were

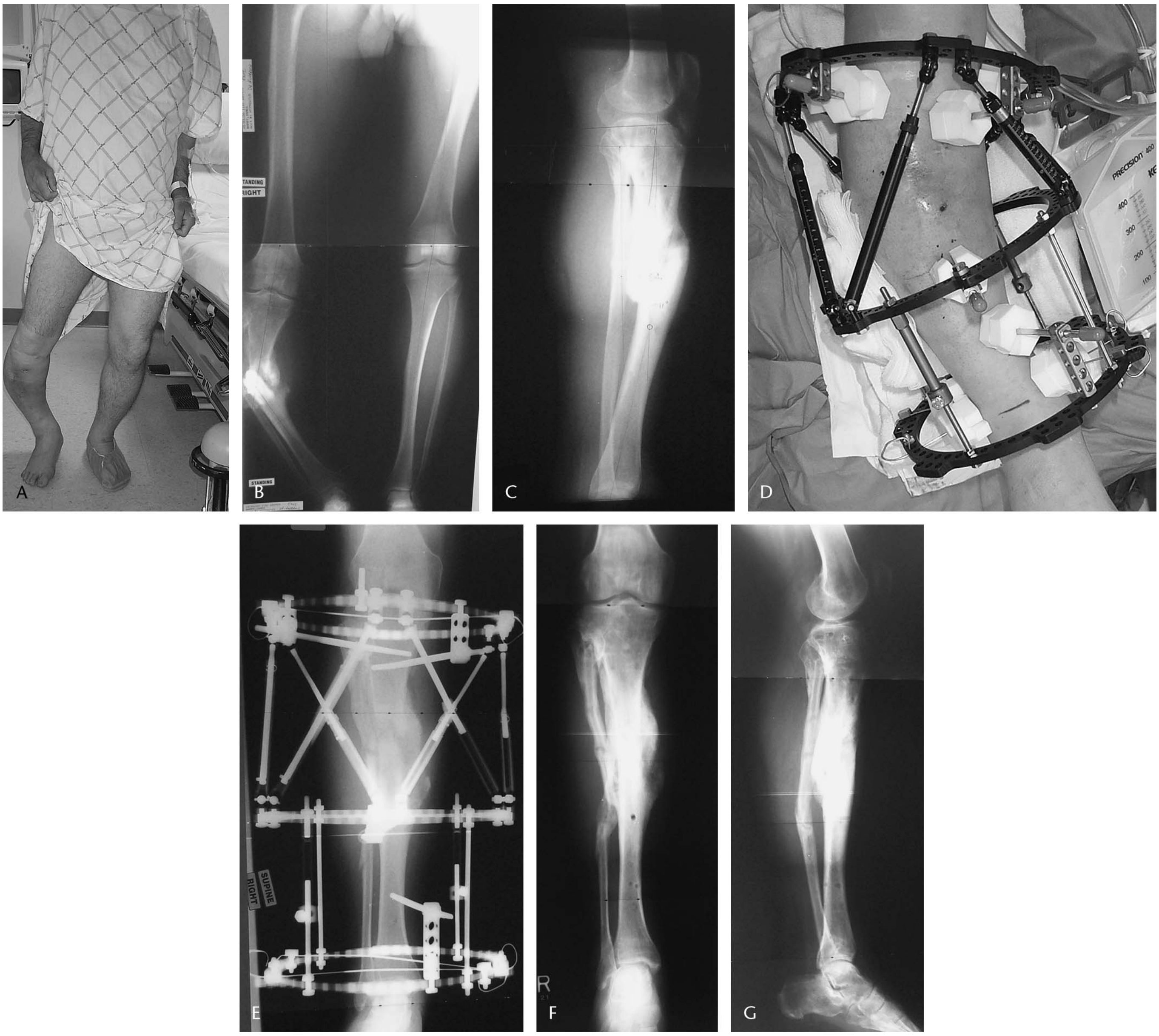

FIGURE 1. A, B, C, Preoperative front view, anteroposterior (AP), and lateral radiographs showing a hypertrophic tibia nonunion with deformity and shortening. D, Immediate postoperative front view showing Ilizarov/Taylor Spatial Frame in place matching the deformity. E, AP radiograph 5 weeks after surgery and distraction of the nonunion. Note that neither osteotomy nor open approach was performed. F, G, AP, lateral radiograph, and front clinical view at 6 months after surgery showing bony union and correction of deformity.

approached in an open fashion. The goals of surgery were to remove all dead bone, open the intramedullary canals, oppose bleeding bone surfaces, and correct the deformity. The nonunion was then mechanically stabilized. With the help of an infectious disease consultant, treatment for chronic osteomyelitis was rendered. This usually consisted of culture-specific intravenous antibiotics for 6 weeks followed by an oral regimen. Bone graft was not used at the primary surgery. Antibiotic beads were used for dead space management and local antibiotic delivery only in the setting of a purulent infection. When debridement of the nonunion resulted in a bone defect, the frame was used for bone transport (Fig. 2) or acute shortening and gradual lengthening.[9,20,22–24,26,36]

When bone transport was used to treat a bone defect, the docking site was prepared when there was about 1 cm of gap. Preparation of the docking site included debridement of fibrous tissue, realignment of bone ends to maximize bony contact and minimize deformity, and addition of bone graft (DBM). This approach has been reported to improve the rate of bony union.[20,22] The site was also cultured to confirm eradication of infection. In some cases, we chose not to bone graft the docking site. Reasons included poor skin and concern of

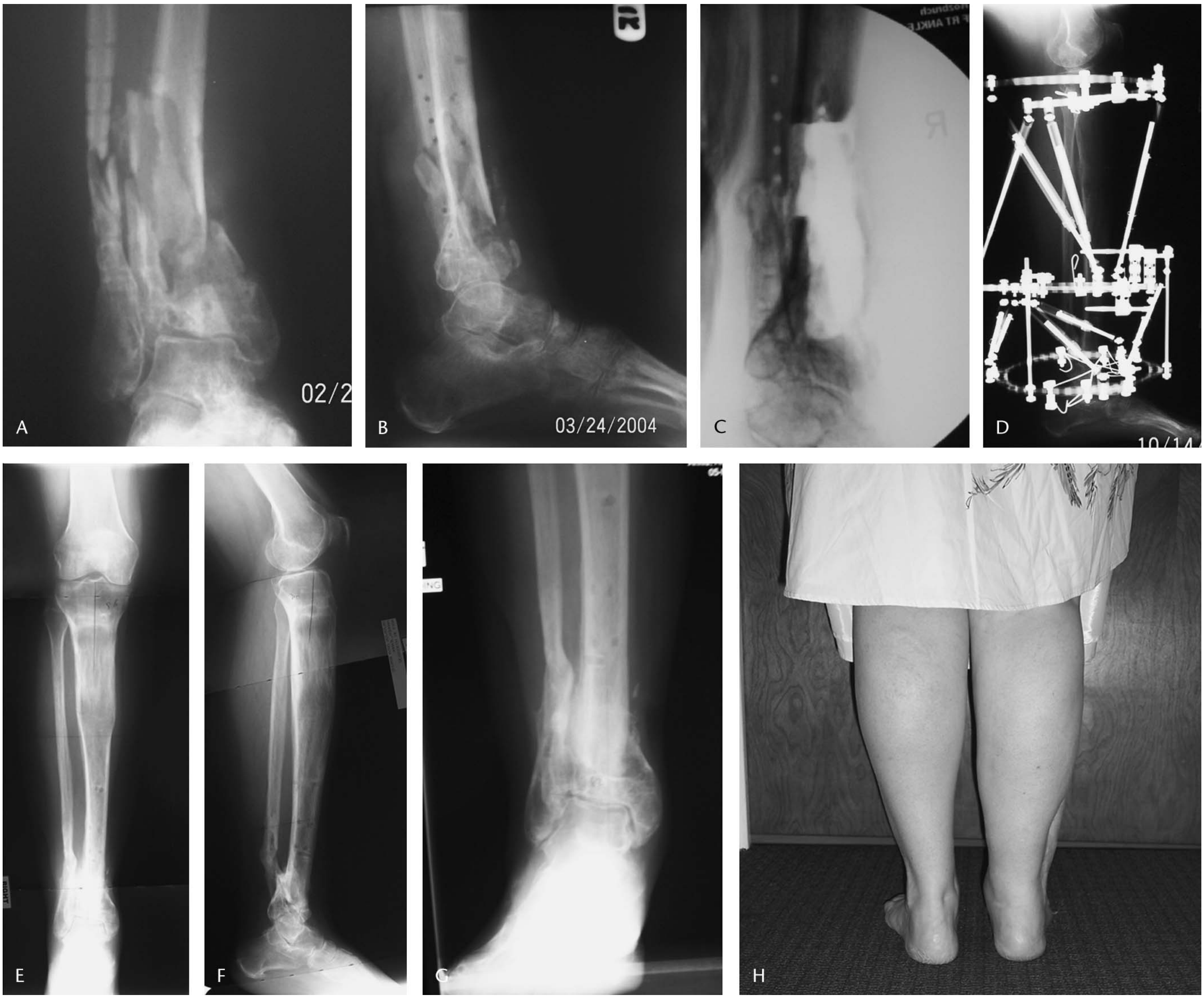

FIGURE 2. A, B, Preoperative AP and lateral radiograph of an infected distal tibia nonunion. C, Intraoperative lateral radiograph after 9-cm excision of necrotic bone. The ankle was preserved with a small segment of distal tibia. D, Lateral radiographs of the mounted TSF showing the proximal tibia lengthening site and the distal tibia docking site at the end of distraction. The TSF was set up to lengthen proximally and compress distally. E, F, AP and lateral radiograph showing the healed proximal tibia lengthening and the distal tibia nonunion (1 year after frame removal). G, AP radiograph showing the healed distal tibia nonunion with preservation of the ankle joint (1 year after frame removal). H, Back view of the patient (1 year after frame removal).

wound problems or a short transport where bone contact was achieved quickly.

The soft-tissue envelope was a critical consideration in treatment. Ten of our patients presented with previous flaps. In the current series, there were 4 large soft-tissue defects. For these, 2 free muscle flaps were performed and 2 patients had gradual bone and soft-tissue transport[26] without a flap. We successfully used the vacuum-assisted closure device to help the open wound granulate during bone transport in 1 of these 2 cases.[38] Acute shortening with or without temporary deformity can also be used to close a wound.[36] It is a matter of philosophy whether the acute or gradual shortening technique should be used as a last resort only when flap coverage is not an option or if it should be used as a first resort to avoid the need for a flap. Flap coverage works well[39,40] with bone transport under a healthy soft-tissue envelope. Acute[36] or gradual[20,26] shortening can be successful and avoid the need for a flap. The final choice will depend on the surgeon's preference, patient factors, and availability of plastic surgery expertise. We are more likely to choose a flap for a patient with a large soft-tissue defect and to choose acute shortening with angulation for patient with a smaller soft-tissue defect. Other factors such as vascular anatomy and medical comorbidities will also be considerations.

In the current series, bony union was achieved after the initial treatment in 27 (71%) patients. Initial failure was correlated with infection. The lack of correlation with diabetes and smoking is likely related to a small sample of patients. The 11 persistent nonunions were re-treated with TSF reapplication in 4, intramedullary rodding in 3, plate fixation in 2 (Fig. 3), and amputation in 2 patients. Only the 2 patients who were treated with amputation had persistent infection. This resulted in final bony union in 36 (95%) patients. The use of internal fixation to salvage initial failures in 5 patients was not planned. In these patients, complex nonunions were converted into more simple nonunions that could be successfully treated with intramedullary rods or plates. Two patients who had

FIGURE 3. A, AP radiograph of an infected nonunion of distal tibia in a patient who is insulin dependent. Note the shortening of the medial column of the ankle. B, AP radiograph after lengthening of the tibia relative to the fibula to restore malleolar relationship. Six weeks of intravenous antibiotics had been administered. C, AP radiograph that shows a stiff nonunion with medial bone loss after frame removal. Infection was eradicated. D, E, AP and lateral radiographs 2 years after percutaneous plating and bone grafting of the tibia showing bony union.

undergone bone transport and had persistent nonunions at the mid-diaphyseal docking site were successfully treated with closed intramedullary rodding. One patient who had a stiff nonunion at the proximal metaphyseal docking site was successfully treated with a locked plate. One patient (Fig. 3) with an infected distal tibial nonunion with deformity was left with incomplete bony union but with correction of deformity and eradication of infection. Percutaneous plating was effective to help achieve bony union. Although a concern, none of these patients developed infection after insertion of internal fixation. Kocaoglu et al[37] even used bone transport over an intramedullary nail for infected nonunions. They noted decreased time in frame but did report recurrent infection in 2 of 7 (29%) of tibial cases.

The current series is a relatively large group of consecutive nonunions treated with the Ilizarov method and the TSF. The outcomes were similar to other series reported in the literature.[8–10,13,15,20–26,41] This is the largest series in the English language orthopaedic literature of tibial nonunions treated with the TSF. Feldman et al[10] reported their experience with the TSF for 18 nonunions and malunions. There were 7 tibial nonunions in their series. They achieved bony union in 17 of 18 patients.

Infected nonunions have a higher risk of failure than noninfected cases. Dendrinos et al[24] reported on their experience with the Ilizarov technique and frame for treatment of nonunion of the tibia associated with infection in 28 patients. Of the patients, 11% had a problem with union that required bone graft. One patient had a refracture and was ultimately treated with an amputation. Cattaneo et al[9] also reported on 28 patients with infected nonunions and segmental defects treated with the Ilizarov frame. They achieved bony union in all patients. Good to excellent functional results were noted in 21 patients.

LLD and deformity were addressed in all patients. The average final LLD was 1.8 cm. Alignment with deformity less than 5° was achieved in 32 patients and between 6° to 10° was achieved in 4 patients. Our impression is that use of the TSF gives the surgeon better and easier control of bony position than the traditional frame. Also, when dealing with staged deformity correction or need for secondary deformity correction, the TSF modifications are easier and quicker than with the classic Ilizarov frame. Once contact and compression at the nonunion site were achieved, additional stabilization of the TSF was accomplished by adding rods or additional struts to lock the frame. Precise deformity correction[41–45] and ease of use[43,44,46] have been cited by other authors as advantages of the TSF. Kristiansen et al[46] showed that the external fixation index was comparable between the TSF and the classic Ilizarov frame.

This study's limitations include its retrospective nature and small numbers of patients. A randomized prospective study with large numbers of tibial nonunions would help clarify when to choose the TSF versus the classic Ilizarov frame.

One can comprehensively approach tibial nonunions with the TSF. This is particularly useful in the setting of hypertrophic nonunion, infection, bone loss, LLD, and poor soft-tissue envelope. The Ilizarov method is particularly useful for addressing the spectrum of tibial nonunion pathology. The TSF saves time when dealing with complex deformity.

ACKNOWLEDGMENTS

The authors wish to thank Margaret G. E. Peterson, PhD, for her assistance with statistical analysis.

REFERENCES

1. Chin KR, Nagarkatti DG, Miranda MA, et al. Salvage of distal tibia metaphyseal nonunions with the 90 degrees cannulated blade plate. *Clin Orthop Relat Res*. 2003;409:241–249.
2. Helfet DL, Jupiter JB, Gasser S. Indirect reduction and tension-band plating of tibial non-union with deformity. *J Bone Joint Surg Am*. 1992; 74:1286–1297.
3. Rosen H. Compression treatment of long bone pseudarthroses. *Clin Orthop Relat Res*. 1979;138:154–166.
4. Court-Brown CM, Keating JF, Christie J, et al. Exchange intramedullary nailing. Its use in aseptic tibial nonunion. *J Bone Joint Surg Br*. 1995;77: 407–411.
5. Moed BR, Watson JT. Intramedullary nailing of aseptic tibial nonunions without the use of the fracture table. *J Orthop Trauma*. 1995;9:128–134.
6. Richmond J, Colleran K, Borens O, et al. Nonunions of the distal tibia treated by reamed intramedullary nailing. *J Orthop Trauma*. 2004;18: 603–610.
7. Templeman D, Thomas M, Varecka T, et al. Exchange reamed intramedullary nailing for delayed union and nonunion of the tibia. *Clin Orthop Relat Res*. 1995;315:169–175.
8. Catagni MA, Guerreschi F, Holman JA, et al. Distraction osteogenesis in the treatment of stiff hypertrophic nonunions using the Ilizarov apparatus. *Clin Orthop Relat Res*. 1994;301:159–163.
9. Cattaneo R, Catagni M, Johnson EE. The treatment of infected nonunions and segmental defects of the tibia by the methods of Ilizarov. *Clin Orthop Relat Res*. 1992;280:143–152.
10. Feldman DS, Shin SS, Madan S, et al. Correction of tibial malunion and nonunion with six-axis analysis deformity correction using the Taylor Spatial Frame. *J Orthop Trauma*. 2003;178:549–554.
11. Green SA, Garland DE, Moore TJ, et al. External fixation for the uninfected angulated nonunion of the tibia. *Clin Orthop Relat Res*. 1984; 190:204–211.
12. Ilizarov GA. Clinical application of the tension-stress effect for limb lengthening. *Clin Orthop Relat Res*. 1990;250:8–26.
13. Kocaoglu M, Eralp L, Sen C, et al. Management of stiff hypertrophic nonunions by distraction osteogenesis: a report of 16 cases. *J Orthop Trauma*. 2003;17:543–548.
14. Menon DK, Dougall TW, Pool RD, et al. Augmentative Ilizarov external fixation after failure of diaphyseal union with intramedullary nailing. *J Orthop Trauma*. 2002;16:491–497.
15. Rozbruch SR, Helfet DL, Blyakher A. Distraction of hypertrophic nonunion of tibia with deformity using Ilizarov/Taylor Spatial Frame. Report of two cases. *Arch Orthop Trauma Surg*. 2002;122:295–298.
16. Rozbruch SR, Herzenberg JE, Tetsworth K, et al. Distraction osteogenesis for nonunion after high tibial osteotomy. *Clin Orthop Relat Res*. 2002; 394:227–235.
17. Schatzker J. Osteosynthesis in trauma. *Int Orthop*. 1996;20:244–252.
18. Ilizarov GA. *Transosseous Osteosynthesis*. 1st ed. Berlin: Springer-Verlag; 1992.
19. Saleh M, Royston S. Management of nonunion of fractures by distraction with correction of angulation and shortening. *J Bone Joint Surg Br*. 1996; 78:105–109.
20. Paley D, Maar DC. Ilizarov bone transport treatment for tibial defects. *J Orthop Trauma*. 2000;14:76–85.
21. Pugh K, Rozbruch SR. Nonunions and malunions. In: Baumgaertner MR, Tornetta P, eds. *Orthopaedic Knowledge Update Trauma 3*. Rosemont, IL: American Academy of Orthopaedic Surgeons; 2005:115–130.
22. Song HR, Cho SH, Koo KH, et al. Tibial bone defects treated by internal bone transport using the Ilizarov method. *Int Orthop*. 1998;22:293–297.
23. Paley D, Catagni MA, Argnani F, et al. Ilizarov treatment of tibial nonunions with bone loss. *Clin Orthop Relat Res*. 1989;241:146–165.
24. Dendrinos GK, Kontos S, Lyritsis E. Use of the Ilizarov technique for treatment of non-union of the tibia associated with infection. *J Bone Joint Surg Am*. 1995;77:835–846.
25. Marsh DR, Shah S, Elliott J, et al. The Ilizarov method in nonunion, malunion and infection of fractures. *J Bone Joint Surg Br*. 1997;79:273–279.

26. Rozbruch SR, Weitzman AM, Watson JT, et al. Simultaneous treatment of tibial bone and soft-tissue defects with the Ilizarov method. *J Orthop Trauma*. 2006;20:197–205.
27. Paley D. *Principles of Deformity Correction*. 1st ed. Berlin: Springer-Verlag; 2005.
28. Paley D, Herzenberg JE, Tetsworth K, et al. Deformity planning for frontal and sagittal plane corrective osteotomies. *Orthop Clin North Am*. 1994; 25:425–465.
29. Rozbruch SR, Blyakher A, Haas SB, et al. Correction of large bilateral tibia vara with the Ilizarov method. *J Knee Surg*. 2003;16:34–37.
30. Shtarker H, Volpin G, Stolero J, et al. Correction of combined angular and rotational deformities by the Ilizarov method. *Clin Orthop Relat Res*. 2002;402:184–195.
31. Fragomen A, Ilizarov S, Blyakher A, et al. Proximal tibial osteotomy for medial compartment osteoarthritis of the knee using the Taylor Spatial Frame. *Techn Knee Surg*. 2005;4:175–183.
32. Nolte PA, van der KA, Patka P, et al. Low-intensity pulsed ultrasound in the treatment of nonunions. *J Trauma*. 2001;51:693–702.
33. Scott G, King JB. A prospective, double-blind trial of electrical capacitive coupling in the treatment of non-union of long bones. *J Bone Joint Surg Am*. 1994;76:820–826.
34. Gardner MJ, Toro-Arbelaez JB, Boraiah S, et al. Surgical treatment and outcomes of extraarticular proximal tibial nonunions. *Arch Orthop Trauma Surg*. 2007[Epub ahead of print].
35. Maurer DJ, Merkow RL, Gustilo RB. Infection after intramedullary nailing of severe open tibial fractures initially treated with external fixation. *J Bone Joint Surg Am*. 1989;71:835–838.
36. Nho SJ, Helfet DL, Rozbruch SR. Temporary intentional leg shortening and deformation to facilitate wound closure using the Ilizarov/Taylor spatial frame. *J Orthop Trauma*. 2006;20:419–424.
37. Kocaoglu M, Eralp L, Rashid HU, et al. Reconstruction of segmental bone defects due to chronic osteomyelitis with use of an external fixator and an intramedullary nail. *J Bone Joint Surg Am*. 2006;88:2137–2145.
38. Wongworawat MD, Schnall SB, Holtom PD, et al. Negative pressure dressings as an alternative technique for the treatment of infected wounds. *Clin Orthop Relat Res*. 2003;414:45–48.
39. Gayle LB, Lineaweaver WC, Oliva A, et al. Treatment of chronic osteomyelitis of the lower extremities with debridement and microvascular muscle transfer. *Clin Plast Surg*. 1992;19:895–903.
40. Lowenberg DW, Feibel RJ, Louie KW, et al. Combined muscle flap and Ilizarov reconstruction for bone and soft tissue defects. *Clin Orthop Relat Res*. 1996;332:37–51.
41. Tsuchiya H, Morsy AF, Matsubara H, et al. Treatment of benign bone tumours using external fixation. *J Bone Joint Surg Br*. 2007;89B:1077–1083.
42. Al Sayyad MJ. Taylor Spatial Frame in the treatment of pediatric and adolescent tibial shaft fractures. *J Pediatr Orthop*. 2006;26: 164–170.
43. Eidelman M, Bialik V, Katzman A. Correction of deformities in children using the Taylor spatial frame. *J Pediatr Orthop B*. 2006;15: 387–395.
44. Feldman DS, Madan SS, Ruchelsman DE, et al. Accuracy of correction of tibia vara: acute versus gradual correction. *J Pediatr Orthop*. 2006;26: 794–798.
45. Rogers MJ, McFadyen I, Livingstone JA, et al. Computer hexapod assisted orthopaedic surgery (CHAOS) in the correction of long bone fracture and deformity. *J Orthop Trauma*. 2007;21:337–342.
46. Kristiansen LP, Steen H, Reikeras O. No difference in tibial lengthening index by use of Taylor spatial frame or Ilizarov external fixator. *Acta Orthop*. 2006;77:772–777.

