Combined Technique for the Treatment of Infected Nonunions of the Distal Femur With Bone Loss: Short Supracondylar Nail–Augmented Acute Shortening/Lengthening

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Objective: To evaluate a combined technique for treating distal femoral bone defects after debridement of osteomyelitis, using an external fixator together with a short supracondylar nail.

Design: Retrospective study.

Setting: Single tertiary referral center.

Methods: Between 2003 and 2018, 23 patients with a mean age of 37.2 years (26–56) underwent surgery with the same technique to manage postdebridement defects in the distal femur due to osteomyelitis. This involved acute shortening and intramedullary fixation of the defect site, together with relengthening from a proximal osteotomy using simultaneous external fixation. Radiographic union, range of motion of the hip and knee, external fixation time and external fixation index, and limb length discrepancy were assessed.

Results: The mean follow-up was 51 months (18–192). Union was achieved in all patients without recurrence of infection during this follow-up period. The mean knee flexion was 120 degrees, and the mean extension deficit was 5 degrees at final follow-up. The mean limb length discrepancy improved from 5.5 cm (3–7) to 0.5 cm (0–2). The mean external fixation index was 29.2 d/cm (20–50), and the mean external fixation time was 115 days (90–150). Radiographic scores were excellent in 15 cases, good in 6, and fair in 2. Functional scores were excellent in 14 cases, good in 7, and fair in 2.

Conclusion: This combined strategy was an effective method for treating distal femoral segmental bone defects after debridement of osteomyelitis, with a high rate of union and acceptable complication rates.

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INTRODUCTION

Successful treatment of chronic osteomyelitis is generally dictated by the quality of the debridement.[1–5] This requires resection of all infected and necrotic material, often resulting in significant bone and soft tissue defects. These patients have typically already undergone many previous operations, and the local anatomy may be grossly distorted and heavily invested with dense scar.[3,4] The stakes are high, and the risk of vascular or neurological injury makes any additional surgical procedures even more challenging.

With superimposed shortening, angular deformities, soft-tissue deficiencies, and segmental skeletal defects, these clinically daunting cases can still be effectively treated using a variety of techniques.[1–4] Distraction osteogenesis[2,4,6,7] is an attractive option and can simultaneously manage the pseudoarthrosis, limb length discrepancy (LLD), and any other associated deformities.[6,7] Bifocal osteosynthesis is typically used, with compression at one site and simultaneous distraction at another within the same bone segment. This can be achieved by either bone transport or acute shortening/lengthening, regenerating bone from a healthy unaffected region.[8–17] However, one of the major problems with this type of treatment is the potential for delays in bone healing at the compression site, and this can increase the external fixation time (EFT) necessary. Although prolonged external fixation of the tibia in adults is reasonably well tolerated, when the femur is involved, it is considered more difficult and arduous for the patient to endure.

To attempt to diminish this risk of prolonged femoral external fixation, and to reduce the rate of nonunion at the original defect site, a combined technique was introduced incorporating simultaneous intramedullary fixation distally.

Treatment with this hybrid technique involves acute compression of the defect site over a short retrograde supracondylar nail, together with concurrent lengthening through a proximal femoral corticotomy using a unilateral external fixator (EF).

In this study, we evaluated the results using this technique in a consecutive series of 23 patients with posttraumatic distal femoral segmental bone defects after debridement of osteomyelitis. The hypothesis was that this surgical technique would result in better outcomes compared with historical controls. The primary outcome of this study was solid union distally, with secondary outcomes including the eradication of infection, restoration of limb length, and consolidation of the proximal distraction site.

METHODS

This retrospective cohort study was conducted on a consecutive series of patients treated using this combined technique between March 2003 and January 2018. Approval to undertake this investigation was granted by our institutional Human Research Ethics Committee, and the study performed according to STROBE guidelines.[18] Patients treated using this technique were identified through an electronic database in our department. The inclusion criteria: adults; chronically infected nonunions of the distal femur; posttraumatic skeletal defect after osteomyelitis debridement; treated using this combined technique; and minimum follow-up 18 months. The exclusion criteria: Cierny-Mader[1] C hosts (morbidity of treatment greater than the morbidity of their disease); bone defects >10 cm; age over 60 years; body mass index over 40; and heavy smokers. All patients were managed under the same treatment protocol, with 2-staged surgical debridement and appropriate antibiotic coverage. The surgical procedure involves debridement with resection of an infected nonunion of the distal femur. The defect site is acutely compressed and stabilized using a statically locked short supracondylar intramedullary nail, in combination with concurrent proximal lengthening using a monolateral EF.

Medical charts and radiographs were reviewed, and the demographic characteristics (age, sex, previous surgeries, and length of follow-up) and clinical outcomes [postoperative knee range of motion (ROM), complications] were recorded. The EFT (in months) and the external fixation index (EFI: EFT divided by the amount of lengthening achieved in cm)[19] were noted. Local or systemic signs of infection, including persistent erythema, active drainage, wound dehiscence, or positive cultures, were all considered adequate for diagnosis of infection, both before and after treatment. Radiographic characteristics were documented, including the extent of any LLD after acute compression, during the early postoperative period, and at their latest follow-up. Radiographic union of the docking site was defined as bridging callus on at least 3 of the 4 cortices on plain radiographs, or obliteration of the fracture line.[20] Bone and functional results were evaluated using the criteria of Paley et al,[21,22] and complications were classified according to Paley.[23] Means were calculated for continuous variables, but given the small sample size and lack of groups for comparison, no formal statistical analysis was performed.

SURGICAL TECHNIQUE

The acute compression/concurrent distraction (lengthening) combined technique involves closing the gap created by resection of the infected bone segment, followed by gradual lengthening through an osteotomy located in normal healthy bone.[14,17,24] The local biological environment at the resection site is often severely compromised from the original trauma and subsequent surgeries, and the acutely compressed bone is prone to nonunion or delayed union.[17] To address this problem, this procedure augments fixation of the acute compression site using a short locked supracondylar nail, together with lengthening of the femur through healthy proximal bone using an EF.

The anticipated extent of resection of infected or necrotic bone was determined preoperatively using both plain radiographs and T2-weighted magnetic resonance imaging.[3,4,25,26] Magnetic resonance imaging was also used to determine whether any skip lesions were present independent of main focus of infection.[25,26] Intraoperatively, surgical resection margins were determined based on the clinical acumen of experienced surgeons, together with the available preoperative imaging.[3,4] Preoperative and perioperative Doppler ultrasound examination is required to assess any potential vascular insufficiency, particularly after the acute shortening.

During the first stage, surgical debridement of the infected nonunion was undertaken, adhering to established principles for staged management of osteomyelitis.[1–4] Existing implants were removed, and necrotic or infected bone segments were resected until punctate Haversian bleeding was observed. Infected scarred soft tissue was debrided and tissue samples were taken for cultures, to identify the responsible organisms and to select appropriate antibiotics. The dead space was filled with bespoke antibiotic impregnated beads or rods, containing 2 g of powdered vancomycin per 40 g of polymethylmethacrylate (PMMA). Temporary femoral fixation was provided by either an EF, or a custom-made brace in those patients with a PMMA antibiotic intramedullary rod. After the first stage, patients received 6 weeks of pathogen-specific antibiotic therapy, 3 weeks intravenously and another 3 weeks orally. Definitive reconstruction was planned as the second stage when infection was controlled according to clinical signs and inflammatory markers, including the C-reactive protein level and erythrocyte sedimentation rate.

During this second stage, the antibiotic PMMA rod or beads were removed, and the debridement repeated with reaming of the medullary canal. Acute shortening of the segmental defect was performed, monitoring the arterial circulation distally. The acute shortening was limited to less than 7 cm, to minimize the potential for arterial occlusion or venous congestion immediately after the procedure.[17] Osteosynthesis was achieved using a short, retrograde, supracondylar nail initially only locked distally, and left free proximally. A monolateral EF was then applied to the femur, and a more proximal percutaneous osteotomy was performed

using multiple drill-holes[27] (Figs. 1 and 2). For defects between 7 and 10 cm, shortening of 7 cm was completed acutely, with the remainder closed gradually at a rate of 2–3 mm/d until compression was achieved at the docking site.[17] The docking site was actively compressed over the nail using the EF for several weeks; once early callus was visible, the nail was locked proximally and then allowed to heal further, while distraction proximally was used to restore length.

After a latency period of 7 days,[6,7] distraction of the proximal osteotomy was begun at a rate of 1 mm/d in 4 divided increments. Routine radiographs and clinical evaluations were completed every 2 weeks during the distraction phase and every month during the consolidation phase. Distraction was stopped after the length of the femur was restored. The EF was removed when consolidation of at least 3 cortices was confirmed radiographically (Fig. 3).

RESULTS

A total of 23 patients were identified who met the inclusion criteria (6 women and 17 men), with a mean age of 37.2 years (26–56). The mean number of previous surgeries was 2.6 (1–5), and the mean follow-up period was 51 months (18–192). The etiology of the chronic osteomyelitis was post-traumatic in 17, hematogenous in 2, and a gunshot wound in 4. All 23 patients were classified as Cierny–Mader[1] type IVA and type IVB osteomyelitis, with infected nonunions of the distal femur.

The debridement site healed completely in all 23 patients, without any recurrence of infection at the time of their most recent clinical review. The mean LLD improved from 5.5 cm (3–7) to 0.5 cm (0–2) and in no case was the residual LLD >2 cm after treatment. The mean knee flexion was 120 degrees (90–130 degrees), and the mean extension deficit was 5 degrees (0–20 degrees). The mean EFI was 29.2 d/cm (20–50), and the mean EFT was 115 days (90–150) (Table 1). The radiographic bone score[21,22] was excellent in 15 cases, good in 6, and fair in 2, and the functional scores[21,22] were excellent in 14 cases, good in 7, and fair in 2 (Table 2).

Adverse events were classified as described by Paley,[23] with a mean of 1 complication per patient. The most common complication was pin-tract infection,[12] although pin removal/exchange was necessary in only 2 patients. The remaining pin site infections were clinically controlled with daily wound dressings and oral antibiotics. Other complications included mild angulation of the regenerate in one patient and decreased knee ROM in 8 patients.

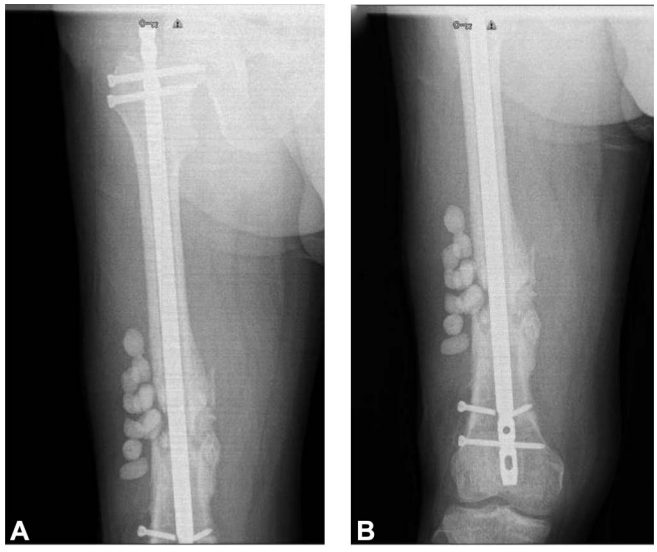

FIGURE 1. A 56-year-old man sustained an R femoral shaft fracture in an MVA, initially managed at an outside hospital with an antegrade IM nail. He was later referred to our center with an infected nonunion that had previously undergone débridement and insertion of antibiotic PMMA beads [AP radiographs, proximal (A), and distal (B)], without removal of the original implant. AP, antero-posterior; IM, intramedullary; MVA, motor vehicle accident.

DISCUSSION

The most important finding of this study was that solid union was achieved and infection was clinically eradicated in all 23 of these difficult cases. The addition of a short retrograde supracondylar nail through the area of the original infected nonunion, to augment stability at the acute shortening site, was a useful adjunct biomechanically. When

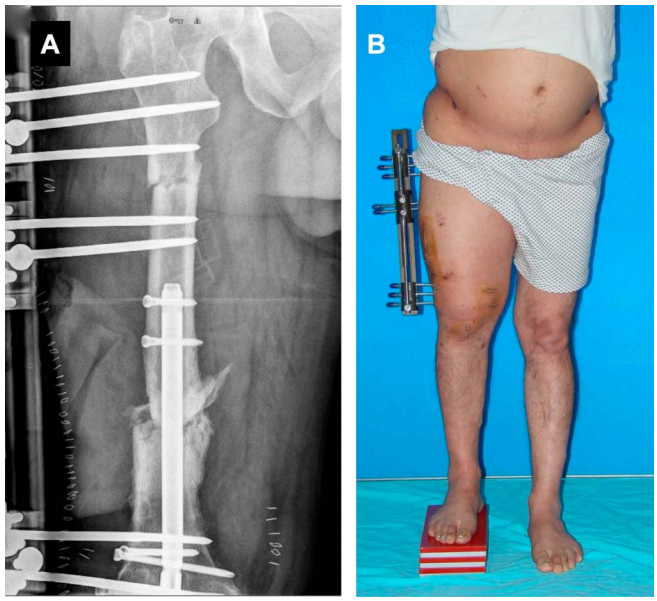

FIGURE 2. Six months after the index surgery, he was treated by open débridement, with removal of all implants and necrotic bone. In this case, the reconstruction was completed as a single-stage procedure; the ensuing segmental defect was acutely shortened 7 cm, and a retrograde supracondylar nail was inserted across the acute shortening docking site. Autogenous cancellous bone graft from the iliac crest was added at the junction, and a monolateral rail external fixator was applied laterally [AP radiograph (A), and clinical photograph (B)]. A subtrochanteric corticotomy was performed, and after a latency period of 7 days, gradual distraction at a rate of 1 mm/d (0.25 mm qid) was used to eliminate the leg length discrepancy. AP, antero-posterior. **Editor's Note**: A color image accompanies the online version of this article.

FIGURE 3. Final radiographs [AP (A) and lateral (B)], demonstrating solid union distally, and very satisfactory alignment. Final clinical photographs after fixator removal, demonstrating very good cosmesis and equal leg lengths (C), full extension of his knee (D), and 105 degrees of knee flexion (E). AP, antero-posterior. **Editor's Note**: A color image accompanies the online version of this article.

performed as a staged procedure, the introduction of a large intramedullary metallic implant into a previously infected area had no apparent detrimental effect.[2]

To successfully treat and cure chronic osteomyelitis of the femur requires meticulous debridement, with removal of all necrotic bone and soft tissue until only viable, bleeding tissue remains.[1–4] Radical debridement often creates further bone and soft-tissue defects that may then require complex reconstruction using techniques such as bone transport or lengthening. This requires another osteotomy within the healthy part of the femur proximally, to regenerate bone through either lengthening or transport. However, this method introduces additional potential risks such as nonunion, infection, refracture, or deformity through the region of regenerated bone.

To achieve consistent union of the previously infected nonunion site can be notoriously difficult, with segmental defects and limb length discrepancies present after completing the requisite debridement. To decrease the risk of nonunion of the docking site distally, a short retrograde intramedullary nail was inserted, statically locked proximally and distally after acute compression of the defect site. The potential for arterial occlusion or venous congestion during or after the procedure was minimized by limiting the magnitude of the acute shortening to less than 7 cm.[17] Lengthening to correct the resulting LLD was then accomplished through healthy unaffected bone in the proximal femoral diaphysis. All these patients had type IV osteomyelitis, and aggressive debridement was required followed by pathogen-specific local and systemic antibiotic treatment in a standard protocol.[1–4] In this study, union with an acceptable residual LLD was achieved in all 23 patients without clinical recurrence of the infection during the follow-up period.

Many alternative treatment methods have been described to address the bone defect resulting from debridement of an infected nonunion, including conventional cancellous bone grafting,[28] vascularized fibula transfers,[29] and the Masquelet-induced membrane technique.[30] However, residual LLD and deformity issues of sufficient magnitude to potentially affect the activities of daily living still remain unresolved with many of these methods.[1,6,22] Distraction osteogenesis solves many of the technical problems related to the definitive reconstruction after chronic osteomyelitis and its consequences, such as nonunion, deformity, LLD, and contractures.[6,8–17,21,22,31–34] Ilizarov originally developed the concept and technique of bone transport,[7] although Paley et al[21] in 1989 were the first to report (in English) successful results using this method to treat tibial nonunions and osteomyelitis with bone loss. Since then, many others have demonstrated the efficacy of this technique.[8,10,12,15–17,22,31,33–39] Despite this, there are still some disadvantages and technical difficulties associated with bone transport, including the possibility of delayed union or nonunion at

TABLE 1. Clinical Outcomes

Union	23/23 (100%)
Recurrent infection	0/23 (0%)
LLD preoperative	5.5 cm (3–7)
LLD postoperative	0.5 cm (0–2)
Knee extension	5 degrees (0–20 degrees)
Knee flexion	120 degrees (90–130 degrees)
EFI	29.2 d/cm (20–50)
EFT	115.0 d (90–150)

Standard clinical outcomes reflecting the results obtained in this study cohort. Most importantly, in this study cohort, clinical and radiographic union was achieved in all patients, and infection was arrested or clinically quiescent in all patients.

TABLE 2. Paley Scoring/Outcomes

	Bone Score	Functional Score
Excellent	15	14
Good	6	7
Fair	2	2
Poor	0	0
Total	23	23

Radiographic and functional outcome summary scores using the criteria described by Paley et al in previous publications.[21,22] There were 91.3% excellent/good results achieved across this study group for both the radiographic criteria and when using clinical outcome criteria.

the docking site. The combined technique described here, incorporating acute compression over a short retrograde nail and concurrent distraction with a monolateral EF, appears to have genuine advantages, probably related to the more stable intramedullary fixation at the docking site.

The acute shortening method was first described by Giebel[40] in 1991 for the treatment of tibial pseudarthrosis with bone loss. Sen et al[24] reported the first case series of acute shortening/lengthening for the treatment of tibial pseudarthrosis with bone loss. In the current study, static intramedullary fixation of the docking site after acute shortening was added to the technique. Although advanced technologies such as telescopic nails can now achieve similar results using different techniques that do not require prolonged external fixation, these implants are expensive and may not be available in a resource limited environment. The technique described here is simple, widely available, and much less expensive to implement, and this approach is still an attractive alternative in health care systems that are financially constrained.

Kocaoglu et al[41] first described femoral bone transport over an intramedullary nail, with the intent to decrease the EFT. Although the technique of transport over a nail has several potential advantages, including decreased EFT and protection against regenerate fractures and deformity, it also has several disadvantages. A second procedure is required for locking the nail, and a smaller diameter nail is necessary to facilitate the bone transport.[42] In this study, the largest possible supracondylar nail was used, creating more stable distal fixation and enhancing the potential for rapid union. Rozbruch et al[43] used an alternative strategy, intramedullary nailing after lengthening with an EF (lengthening and then nailing), although this technique has a risk of disseminated deep infection and refracture.[44] Kocaoglu et al[41] reported removal of the nail in 2 (17%) patients due to return of the infection, but in this study cohort, there were no recurrent infections. However, if there had been a recurrence of infection, it would more likely coincide with the location of the intramedullary nail and would therefore be expected to affect only the distal portion of the bone.

Acute femoral shortening, with subsequent lengthening from a different location, clearly distorts normal anatomy locally. Shortening of any amount changes the usual relationship between length, active contraction, and the functional capacity of any muscles involved. Considering these inevitable effects on muscle function, the magnitude of the shortening in this series of cases was limited to a maximum of 7 cm. In addition, distraction osteogenesis procedures themselves may adversely affect muscle function, and in animal models, this response is more pronounced in adults.[45,46] Initiating early active physiotherapy must, therefore, also be a priority in the functional rehabilitation of these patients, to maintain and recover muscle pliability and strength. However, in this series, shortening through the tendinous portion and lengthening through the more proximal sarcomere region consistently achieved excellent and good functional results. Detrimental effects on function of the extremity would be expected to be most evident during treatment and in the first 6–8 weeks after removal of the EF. It is therefore very important to maintain hip and knee ROM with active physical therapy during this period. In our opinion, the more stable fixation obtained with an intramedullary nail in the distal femur may have also helped patients initiate early aggressive physical therapy during lengthening.

The most important limitation of this study was its retrospective nature, and it is therefore potentially susceptible to selection bias, performance bias, and recall bias. Patients were not randomized to this treatment compared with any other group, and selection bias may have influenced the results reported here in a manner difficult to predict. Recall bias could be introduced because complications were not identified prospectively or recorded contemporaneously and therefore may have been underreported. Measurement bias could have occurred, but having a single experienced observer assess all radiographs minimized this possibility. Because this study was conducted at a single academic center, it has only limited generalizability, and these outcomes may not fully transfer to other surgeons or institutions. Finally, the small sample size is an obvious limitation, characteristic of all studies that involve relatively uncommon pathology.

CONCLUSIONS

Treatment of femoral osteomyelitis is challenging, and patients often have poor quality bone and soft tissue due to the original trauma, chronic infection, and multiple previous surgical interventions. Eradication of infection and solid union are the primary aims, with further goals of minimizing any deformity or residual LLD. The results in this series of 23 consecutive cases support the use of this technique for the treatment of distal femoral segmental bone defects resulting from post-traumatic osteomyelitis. Considering the implications of shortening with respect to muscle function, the magnitude of the acute shortening in this series of cases was limited to 7 cm maximum. Clinical control of infection was uniformly obtained, with a very high rate of union and an acceptable risk of complications. The strategy of acute shortening of the distal femur over a short, static, retrograde supracondylar nail combined with lengthening through a more proximal corticotomy using a unilateral fixator was very effective. This hybrid procedure may provide greater patient satisfaction by stabilizing the distal femoral segment to encourage rapid union, while facilitating early motion to enhance functional outcomes after definitive reconstruction.

REFERENCES

1. Cierny G, Mader JT, Penninck JJ. A clinical staging system for adult osteomyelitis. *Contemp Orthop.* 1985;10:17–37.
2. Cierny G. Infected tibial nonunions (1981–1995). The evolution of change. *Clin Orthop Relat Res.* 1999;360:97–105.
3. Tetsworth K, Cierny G. Osteomyelitis debridement techniques. *Clin Orthop Relat Res.* 1999;360:87–96.
4. Heitmann C, Patzakis MJ, Tetsworth KD, et al. Musculoskeletal sepsis: principles of treatment. *Instr Course Lect.* 2003;52:733–744.
5. Simpson AH, Deakin M, Latham JM. Chronic osteomyelitis: the effect of the extent of surgical resection on infection-free survival. *J Bone Joint Surg Br.* 2001;83B:403–407.
6. Aronson J. Limb-lengthening, skeletal reconstruction, and bone transport with the Ilizarov method. *J Bone Joint Surg Am.* 1997;79:1243–1258.

7. Ilizarov GA. Clinical application of the tension-stress effect for limb lengthening. *Clin Orthop Relat Res.* 1990;250:8–26.
8. Atesalp AS, Basbozkurt M, Erler E, et al. Treatment of tibial bone defects with the Ilizarov circular external fixator in high-velocity gunshot wounds. *Int Orthop.* 1998;22:343–347.
9. 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.
10. Green SA, Jackson JM, Wall DM, et al. Management of segmental defects by the Ilizarov intercalary bone transport method. *Clin Orthop Relat Res.* 1992;280:136–142.
11. Marsh JL, Prokuski L, Biermann JS. Chronic infected tibial nonunions with bone loss. Conventional techniques versus bone transport. *Clin Orthop Relat Res.* 1994;301:139–146.
12. 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.
13. Saleh M, Rees A. Bifocal surgery for deformity and bone loss after lower-limb fractures. Comparison of bone-transport and compression-distraction methods. *J Bone Joint Surg Br.* 1995;77:429–434.
14. Dagher F, Roukoz S. Compound tibial fractures with bone loss treated by the Ilizarov technique. *J Bone Joint Surg Br.* 1991;73:316–321.
15. Sala F, Thabet AM, Castelli F, et al. Bone transport for post-infectious segmental tibial bone defects with a combined Ilizarov/Taylor Spatial Frame technique. *J Orthop Trauma.* 2011;25:162–168.
16. Tetsworth KD, Dlaska CE. The art of tibial bone transport using the Ilizarov fixator: the suspension wire technique. *Tech Orthop.* 2015;30: 142–155.
17. Tetsworth K, Paley D, Sen C, et al. Bone transport versus acute shortening for the management of infected tibial non-unions with bone defects. *Injury.* 2017;48:2276–2284.
18. von Elm E, Altman DG, Egger M, et al. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. *J Clin Epidemiol.* 2008;61:344–349.
19. Fischgrund J, Paley D, Suter C. Variables affecting time to bone healing during limb lengthening. *Clin Orthop Relat Res.* 1994;301:31–37.
20. Shisha T. Parameters for defining efficacy in fracture healing. *Clin Cases Miner Bone Metab.* 2010;7:15–16.
21. Paley D, Catagni MA, Argnani F, et al. Ilizarov treatment of tibial nonunions with bone loss. *Clin Orthop Relat Res.* 1989;241:146–165.
22. Paley D, Maar DC. Ilizarov bone transport treatment for tibial defects. *J Orthop Trauma.* 2000;14:76–85.
23. Paley D. Problems, obstacles, and complications of limb lengthening by the Ilizarov technique. *Clin Orthop Relat Res.* 1990;250:81–104.
24. Sen C, Eralp L, Gunes T, et al. An alternative method for the treatment of nonunion of the tibia with bone loss. *J Bone Joint Surg Br.* 2006;88:783–789.
25. Kaim A, Lederman HP, Bongartz G, et al. Chronic post-traumatic osteomyelitis of the lower extremity: comparison of magnetic resonance imaging and combined bone scintigraphy/immunoscintigraphy with radiolabelled monoclonal antigranulocyte antibodies. *Skeletal Radiol.* 2000;29:378–386.
26. Lederman HP, Kaim A, Bongartz G, et al. Pitfalls and limitations of magnetic resonance imaging in chronic posttraumatic osteomyelitis. *Eur Radiol.* 2000;10:1815–1823.
27. DeBastiani G, Aldegheri R, Renzi-Brivio L, et al. Limb lengthening by callus distraction (callotasis). *J Pediat Orthop.* 1987; 7:129–134.
28. Dugan TR, Hubert MG, Siska PA, et al. Open supracondylar femur fractures with bone loss in the polytraumatized patient—timing is everything! *Injury.* 2013;44:1826–1831.
29. Coulet B, Pflieger JF, Arnaud S, et al. Double-barrel fibular graft for metaphyseal areas reconstruction around the knee. *Orthop Traumatol Surg Res.* 2010;96:868–875.
30. Masquelet AC, Begue T. The concept of induced membrane for reconstruction of long bone defects. *Orthop Clin North Am*. 2010;41:27–37.
31. 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.
32. Cierny G III, Zorn KE. Segmental tibial defects. Comparing conventional and Ilizarov methodologies. *Clin Orthop Relat Res.* 1994;301:118–123.
33. Polyzois D, Papachristou G, Kotsiopoulos K, et al. Treatment of tibial and femoral bone loss by distraction osteogenesis. Experience in 28 infected and 14 clean cases. *Acta Orthop Scand Suppl.* 1997;275:84–88.
34. Liu T, Zhang X, Li Z, et al. Management of combined bone defect and limb-length discrepancy after tibial chronic osteomyelitis. *Orthopedics.* 2011;34:e363–e367.
35. Koettstorfer J, Hofbauer M, Wozasek GE. Successful limb salvage using the two-staged technique with internal fixation after osteodistraction in an effort to treat large segmental bone defects in the lower extremity. *Arch Orthop Trauma Surg.* 2012;132:1399–1405.
36. Kucukkaya M, Karakoyun O, Sokucu S, et al. Femoral lengthening and deformity correction using the Fitbone motorized lengthening nail. *J Orthop Sci.* 2015;20:149–154.
37. Papakostidis C, Bhandari M, Giannoudis PV. Distraction osteogenesis in the treatment of long bone defects of the lower limbs: effectiveness, complications and clinical results; a systematic review and meta-analysis. *Bone Joint J.* 2013;95-B:1673–1680.
38. Borzunov DY. Long bone reconstruction using multilevel lengthening of bone defect fragments. *Int Orthop.* 2012;36:1695–1700.
39. Karargyris O, Polyzois VD, Karabinas P, et al. Papineau debridement, Ilizarov bone transport, and negative-pressure wound closure for septic bone defects of the tibia. *Eur J Orthop Surg Traumatol.* 2014;24:1013–1017.
40. Giebel G. Resection debridement of the lower leg with compensatory callus distraction [in German]. *Unfallchirurg.* 1991;94:401–408.
41. 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.
42. Paley D, Herzenberg JE, Paremain G, et al. Femoral lengthening over an intramedullary nail. A matched-case comparison with Ilizarov femoral lengthening. *J Bone Joint Surg Am.* 1997;79:1464–1480.
43. Rozbruch SR, Kleinman D, Fragomen AT, et al. Limb lengthening and then insertion of an intramedullary nail: a case-matched comparison. *Clin Orthop Relat Res.* 2008;466:2923–2932.
44. Nowotarski PJ, Turen CH, Brumback RJ, et al. Conversion of external fixation to intramedullary nailing for fractures of the shaft of the femur in multiply injured patients. *J Bone Joint Surg Am.* 2000;82:781–788.
45. DeDeyne P. Lengthening of muscle during distraction osteogenesis. *Clin Orthop Relat Res.* 2002;403(suppl):S171–S177.
46. DeDeyne P, Hayatsu K, Meyer R, et al. Muscle regeneration and fiber-type transformation during distraction osteogenesis. *J Ortho Res.* 1999; 17:560–570.