CLINICAL ARTICLE

Role of Perforating Artery Pedicled Neurotrophic Flap in the Treatment of Compound Tissue Defect of Tibia Using the Ilizarov Technique

Yuan-jian Wu, MD[1], Yu-bo Zhang, MD[2], Musha Hamushan, MD[2], Wen-jun Zhang, MD[1], Tao Zhang, MD[1], Xu-jun Li, MD[3], Pei Han, MD[2], Teng-fei Lou, MD[2]

[1]*Orthopaedic Department, Zhujiajiao People's Hospital,* [2]*Orthopaedic Department, Shanghai Jiao Tong University Affiliated Sixth People's Hospital and* [3]*Orthopaedic Department, Minhang Branch, Zhongshan Hospital, Fudan University, Shanghai, China*

Objective: To describe our experience with the combined use of pedicled neurotrophic flap and distraction osteogenesis in the management of complex lower extremity injuries with composite bone and soft tissue defects and assess the functional and cosmetic results of this method.

Methods: A pedicled flap with a marked perforator artery was applied for soft tissue coverage after radical debridement and temporary external fixation. In the second stage, the Ilizarov external fixator was used in place of the temporary external fixator for reconstruction of the segmental bone defect by distraction osteogenesis. Twenty-five patients (16 men and nine women; mean age, 39.2 years) were treated by using this combined technique between 2008 and 2016. All cases were graded initially as Gustilo–Anderson grade IIIB open fractures. The soft tissue defect after radical debridement ranged from 9 cm × 5 cm to 14 cm × 11 cm, and the average size of segmental defect was 5.2 (Range, 2.5–8.5) cm. Seventeen of these patients had a history of local infection. The bone structure and function were evaluated by two independent evaluators using Paley's criteria.

Results: Twenty-five patients were followed up for an average of 28.96 (Range, 15–48) months. The distally based sural neurovascular flap was applied in 13 patients, and the greater saphenous neurocutaneous perforator flap in 12 patients. The flap area ranged from 10 cm × 5 cm to 14 cm × 12 cm. Sufficient coverage of soft tissue defect was achieved in all cases. All flaps survived completely without complications. The bone defects were corrected by a mean lengthening of 6.94 (Range, 4.5–9.5) cm. The residual discrepancy was <1 cm in all cases, which was not clinically significant. The function was evaluated as excellent in 12 patients and good in 13 patients. Bone results were graded as excellent in 18 patients and good in seven patients. Complications during treatment included pain, pin tract infections, ankle midfoot joint stiffness, and docking site nonunion. No recurrence of infection was observed in infected patients. All cases achieved successful limb salvage and satisfactory function recovery without recurrence of infection.

Conclusions: The combined technique of a perforator artery pedicled neurotrophic flap and distraction osteogenesis is an effective alternative approach in the salvage treatment of massively traumatized and chronically infected lower extremities.

Key words: Compound defect; Ilizarov technique; Pedicled flap; Reconstruction; Tibia

Address for correspondence Xu-jun Li, MD, Orthopaedic Department, Minhang Branch, Zhongshan Hospital, Fudan University, Shanghai, China; Email: li_xujun@fudan.edu.cn Pei Han, MD, and Teng-fei Lou, MD, Orthopaedic Department, Shanghai Jiao Tong University Affiliated Sixth People's Hospital, Shanghai, China; Tel: 0086-18930173620 (P. H.) and 0086-18702121780 (T. L.); Email: hanpei_cn@163.com (P. H.) and Email: 1522675605@qq.com (T. L.)
Yuan-jian Wu, Yu-bo Zhang, and Musha Hamushan contributed equally to this work.
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Introduction

High-energy lower extremity fractures with massive soft tissue and bone defects remain a considerable challenge for both orthopaedic and reconstructive plastic surgeons.[1–3] These injuries are typically classified as Gustilo Type III fractures and are commonly related to significant morbidity caused by concomitant vascular and soft-tissue injury[4,5]. Currently, orthopaedists have >30 years of experience dealing with lower limb reconstruction for cases with Gustilo IIIB or IIIC open tibial fractures. However, the decision between attempted limb salvage and early amputation continues to pose a dilemma for both surgeons and patients. Many studies support limb salvage with results that indicated upgraded quality of life, although some studies present poor outcomes, such as debilitated activities of daily life, following limb salvage.[6] Most surgeons would agree that protracted dysvascular limbs or limbs with severe nerve defects are not suitable for limb salvage. Limb salvage seeks to restore limb function. However, when limb salvage is performed, restoration of function and anatomical structure is commonly limited by bone and soft tissue healing. The process can be lengthy and accompanied by risks of infection, deformity, joint contractures, limb length discrepancy, and even amputation.[6]

With the development of microsurgical techniques in recent years, skin flap transplantation has become routine practice for reconstructing massive soft tissue defects of the lower extremity.[7–10] Single-stage reconstruction with an osteocutaneous flap is an alternative for treating such complicated injuries.[11,12] This technique immediately fills bone defects, provides soft tissue coverage, and establishes vascularity to the bony bed. However, several factors hinder the popularity of the technique in clinical settings. The bone grafts usually do not match the tibia, which makes a long non-weight-bearing period inevitable to achieve compensatory hypertrophy. Moreover, a single operation to address soft tissue and bone defects using a single large composite flap or multiple free flaps is not recommended due to the high risk of infection in infected cases. Additionally, this process is associated with a high risk of refracture or nonunion and has an unpredictable outcome. Francel *et al.*[13] have demonstrated that the management of Gustilo III fractures with radical debridement, skin flap transfer, external fixation, and bone grafting may significantly improve the rate of limb salvage. However, the researchers showed that incidence of impaired function of the treated limb—which was caused by nonunion, bone malunion, limb length discrepancy, and angulation deformities—was still high in their patients.

The technique of distraction osteogenesis, which was introduced by Ilizarov, is a biological approach to restore large segmental bone defects. It has been universally applied to the management of non-union, osteomyelitis, deformity, traumatic bone loss, and leg length discrepancy. This technique is based on the biological feature of the bone and the capacity of the neighboring soft tissues to regenerate by tension stress induction. Therefore, it can not only reconstruct the segmental defect but also address the coexisting troubles of limb discrepancy, deformity, and joint contractures.[14–16] However, the associated drawbacks of the technique still limit its overall applicability. Unsatisfactory regeneration that may occur as a result of different causes, poor condition of soft tissues, and infection in the defected area may progress through various stages to restore the defect, especially when it is extensive. Almost all relevant clinical studies conclude that bone transport with distraction osteogenesis is a safe alternative in managing infected and aseptic nonunion of the femur and tibia, despite the complications encountered. Cierny and Zorn[17] compared the outcomes of surgery between 23 patients with segmental tibial defects (average size of 8.5 cm) treated with soft tissue transfer and massive cancellous bone grafts and 21 patients with tibial bone defects (average size of 6.4 cm) treated with distraction osteogenesis using the Ilizarov circular apparatus. They concluded that reconstruction of bone defects using Ilizarov method was safer, faster, easier to perform, and less expensive.

This technique can repair associated soft tissue defects in a one-stage procedure.[18] However, this outcome can only be accomplished under the condition that the soft tissue defect is smaller than the bone defect. Therefore, the bone segment used for bone transport must be covered by vascularized soft tissues in cases with large soft tissue defects. Furthermore, the combination of the two potent approaches in the Ilizarov technique and free tissue transfer for limb salvage are expected to synergize the advantages of both procedures. This combination may lead to an improved functional outcome in patients with Gustilo Type III fractures.

This study sought to describe our experience with the combined use of pedicled neurotrophic flap and distraction osteogenesis in managing complex lower extremity injuries with composite bone and soft tissue defects. Additionally, it sought to assess the functional and cosmetic results of this method and analyze the complications of this technique and discuss the corresponding treatment strategy.

Materials and Methods

Participants

This study was reviewed and approved by the institutional review board of Shanghai Sixth People's Hospital, and informed consent was obtained from all patients. The inclusion criteria: (i) *patients* in this study were initially diagnosed with Gustilo–Anderson grade III open tibial fractures, and they had local destruction with bone and associated soft tissue defects before operation; (ii) the *intervention* was pedicled neurotrophic flap transfer combined with distraction osteogenesis; (iii) *comparison* was between the surgical technique used in this study and other techniques described by other studies; (iv) *outcomes*, including radiographic results, functional results, and complications, were presented in the results section; (v) the *study design* was retrospective. The exclusion criteria included: (i) patients who underwent

femoral transport; (ii) patients with non-reconstructable soft tissue destruction; (iii) poor compliance with postoperative management; (iv) patients who did not consent to this study.

The combined surgical technique of pedicled neurotrophic flap and distraction osteogenesis was applied to 25 patients with high-energy tibial fractures between May 2010 and August 2016 at our hospital. All patients chose this management as an alternative to amputation. The patients were composed of 16 males and nine females with an average age of 39.2 (range, 23–57) years at the time of surgery. The average time from injury to initial surgery at our institution was 9.32 (range, 1–20) weeks. The soft tissue defect after radical debridement ranged from 9 cm × 5 cm to 14 × 11cm^2, and the average size of segmental defect was 5.2 (range, 2.5–8.5) cm. Seventeen of these patients had a history of local infection, which was diagnosed through bacterial culture of pathogenic tissue biopsy.

Surgical Technique

Preoperative Assessment

X-ray radiography, computed tomography (CT), or positron emission tomography-CT (PET-CT) were performed to preoperatively assess the possible extent of the infected or dead tissues.[16] Limb discrepancy and mechanical axis deviation were evaluated using long leg radiographs. Active infection was detected with laboratory examinations, including full blood count, C-reactive protein (CRP) level, and erythrocyte sedimentation rate (ESR).

Radical Debridement and Flap Transfer

Any remaining metal implants from previous surgeries were removed. A temporary external fixator, followed by aggressive debridement of necrotic or infected soft tissues and bones, was performed before the application of the flap cover.

When the wound was considered clean, pedicled flaps with a marked perforator artery were applied for soft tissue coverage (Figures 1 and 2). The choice of flap depended mainly on the defect size and location and required pedicle length. The distally based sural neurovascular fasciocutaneous flap, providing a long pedicle and being nourished by the sural nerve and peroneal artery, was designed to repair the soft tissue defects of the lower leg and ankle. Additionally, the greater saphenous neurocutaneous perforator flap, yielding a relatively short pedicle and being nourished by the greater saphenous vein and saphenous nerve, was applied to cover defects located on the medial and anterior aspects of the injured extremity. The color and temperature of the flaps were monitored to predict perfusion and venous conditions.

Application of the Ilizarov Technique

After the flap had healed and edema subsided, normally 4–6 weeks after the soft tissue reconstruction, an Ilizarov circular or unilateral frame was used in place of the temporary external fixator (Figure 3). However, in six cases, the external fixator was replaced immediately after flap coverage on account of the relatively superior soft tissue conditions.

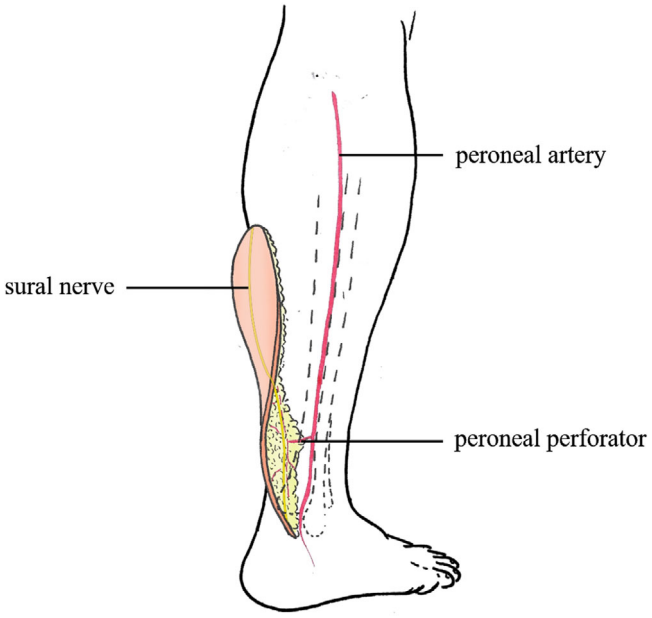

Fig. 1 Schematic diagram of distally based sural neurovascular fasciocutaneous flap which provides a long pedicle and is nourished by the sural nerve and the peroneal artery

Prophylactic antibiotics were administrated intravenously for 1–2 weeks after operation to prevent infection. The selection of antibiotics was targeted to the results of previous bacterial culture. Distraction rate of 4 × 0.25 mm per day was commenced following a latency period of 5–7 days. The compression of the docked ends continued for 5 days after docking for full contact. Moderate range of motion training of the knee and ankle joints was started on the second day postoperatively. Gradual partial weight bearing was encouraged during the process, and full weight bearing exercise was permitted when docking was completed.

Radiographic Measurements

Clinical and radiographic examinations were performed fortnightly during the distraction phase, and monthly during the consolidation phase. Consolidation was considered satisfactory when the formation of a bridging callus was visible on at least three cortices in the anteroposterior and lateral radiographs. If no signs of clinical and radiographical union were present within 3 months after completion of bone contact, bone grafting, resection of atrophic bone ends, or plate fixation replacement was performed. Bone structure and function were evaluated by two independent evaluators with the criteria reported by Paley *et al.*[19].

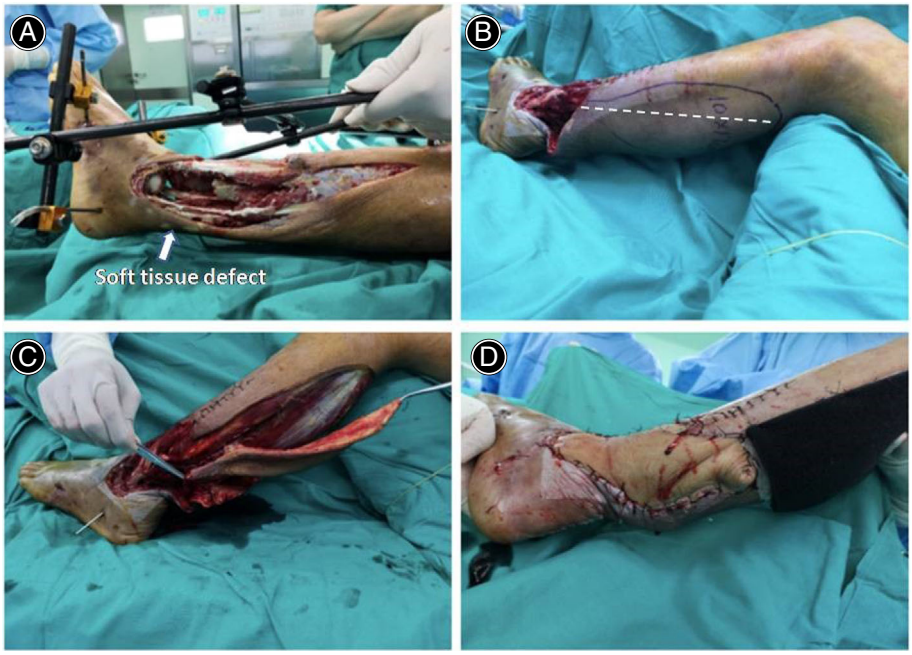

Fig. 2 Patient 2. (A) A temporary external fixator was applied. The soft tissue defect (15 cm × 10 cm) and bone loss (8.5 cm) can be seen. (B) The great saphenous neurocutaneous flap was designed. (C, D) The flap was transferred to cover the soft tissue defect

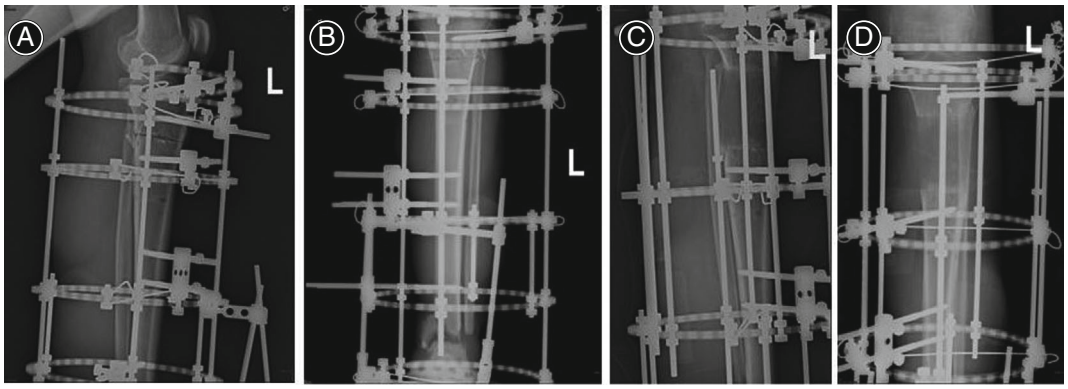

Fig. 3 Patient 2. (A, B) A proximal corticotomy was performed after assembling the Ilizarov circular external fixator. (C, D) New bone formed after distraction osteogenesis

Paley's Evaluation Criteria of Bone Results

The bone results were evaluated based on four criteria: union, infection, deformity, and leg length discrepancy. An excellent result was defined as union, no infection, deformity <7°, and discrepancy of <2.5 cm; good was defined as union and any two of the remaining criteria; fair was defined as union and any one of the remaining criteria; poor was defined as union without any of the three remaining criteria, non-union, or re-fracture.

Functional Measurement

The functional results were evaluated based on five criteria: a conspicuous limp, stiffness of either knee or ankle joint (a loss of over 15° of extension of knee or 15° of dorsiflexion of ankle compared with normal contralateral joint), soft-tissue dystrophy, pain that restrains activity or disrupts sleep, and inability or inactivity to resume daily activities because of injury. The result was considered excellent when a patient is now active and has none of the remaining four criteria, good when a patient is active with any one or two of the remaining four criteria, and fair when a patient is active with three or four of the remaining criteria or has an amputation.[19]

Complication Assessment

Paley's Classification System

Using Paley's classification system, minor complications were defined as problems that do not influence the result or do not require unplanned surgery, whereas major complications

required a more complex additional surgical intervention or result in permanent sequelae.[20]

Dahl's Grading System of Pin Tract Inflammation
Pin tract inflammation was graded according to Dahl's grading system and dealt with accordingly[21]: Grade I, normal pin site; Grade II inflamed; Grade III, inflamed with serous discharge; Grade IV, inflamed with purulent discharge; Grade V, inflamed with osteolysis; Grade VI, inflamed with ring sequestrum.

Results

Twenty-five patients were followed up for an average of 28.96 (Range, 15–48) months. The distally based sural neurovascular flap was applied in 13 patients, and the greater saphenous neurocutaneous perforator flap in 12 patients. The flap area ranged from 10 cm × 5 cm to 14 cm × 12 cm. Sufficient coverage of soft tissue defects was achieved in all cases. All flaps survived completely without complications. The bone defects were remedied by an average lengthening of 6.94 (Range, 4.5–9.5) cm. The residual discrepancy was <1 cm in all cases, which was not clinically significant. No recurrence of infection was found in infected patients.

Paley's Evaluation of Bone and Functional Results

According to the criteria reported by Paley, bone results were evaluated as excellent in 18 cases and good in the remaining seven cases. Functional results were graded as excellent in 12 patients and good in 13 patients. The excellent and good rate was 100%.

Paley's Classification of Complications

Minor complications in our study mainly involved pain (15 patients), pin tract infection (12 patients), and mild ankle midfoot joint stiffness (six patients). Major complications included five cases of nonunion of docking sites. Pain was the most frequent complaint encountered during treatment. In most cases, the patients felt relieved after use of oral analgesics. Two patients found the pain to be intolerable; they were treated effectively with decreased lengthening rate. Six patients developed mild ankle midfoot joint stiffness, which improved after physiotherapy. The docking sites failed to achieve bone union in five patients. Two of the five patients were treated with bone grafting and plate fixation, whereas three of them were treated by refreshing the docking ends.

Dahl's Grading System of Pin Tract Inflammation

Six patients with Grades II (inflamed) and III (inflamed with serous discharge) based on Dahl's classification were present. They responded well to frequent dressing changes and oral antibiotic treatment. Infection of Grade V (inflamed with osteolysis) occurred in one patient who was successfully treated by pin extraction.

Discussion

Advantages of the Combined Technique of Pedicled Neurotrophic Flap and Distraction Osteogenesis

The technique of distraction osteogenesis by Ilizarov is a biological method to reconstruct segmental defects. It has been universally performed for the management of nonunion, osteomyelitis, deformity, traumatic bone loss, and leg length discrepancy. Both microvascular and local flaps can offer soft tissue envelope, increase blood supply, improve bone healing, and defend against infection.[21] According to the basic surgical principles for the management of Gustilo III open fractures, early soft tissue coverage has been proven crucial and effective during treatment.[9–11,18]

Theoretically, a combination of these two powerful techniques could be an ideal method for reconstruction of segmental bone defects complicated by massive loss of soft tissue. The combined surgical technique of artery pedicled neurotrophic flap and distraction osteogenesis was used to treat 25 patients with high-energy tibial fractures graded as Gustilo Type III fractures. All cases achieved successful limb salvage and satisfactory function recovery without recurrence of infection. Additionally, combined free tissue transfer and distraction osteogenesis is an effective method for limb salvage in composite injuries.[10,19] However, the drawbacks of this technique, including long operation time, donor site morbidity, and high technical requirement, should not be ignored. Distraction osteogenesis beneath a free flap would compromise the vascularized tissue.[22,23] Therefore, instead of a free flap, perforator artery pedicled neurotrophic flap, which is simpler and more efficient, was applied to cover massive soft tissue defects. In this study, all flaps survived completely without complications. In addition, disruption of the pedicle resulting from device placement or subsequent distraction was not observed in this study. This outcome was probably due to careful planning, small diameter of the wires, good stabilization of the flap, tolerable distraction rate, and technique of percutaneous placement.

Unlike other surgeons,[24,25] we did not perform temporary acute shortening and subsequent distraction in any case, because this technique causes limb disfigurement and may lead to twist of the vasculature, which may further disrupt the circulation of the mangled fractured extremity.

Comparison between the Combined Technique and Osteocutaneous Flap Transfer

Aside from the surgical technique used in this study, single-stage reconstruction with an osteocutaneous flap is an alternative for treating such complicated injuries.[12,26] This technique immediately fills bone defects, provides soft tissue coverage, and establishes vascularity to the bony bed. However, several factors hinder the popularity of the technique in clinical settings. The bone grafts usually do not match the tibia, which makes a long non-weight-bearing period inevitable to achieve compensatory hypertrophy. Moreover, a single operation to address soft tissue and bone defects using a

single large composite flap or multiple free flaps is not recommended due to the high risk of infection in infected cases. Additionally, this process is associated with a high risk of refracture or nonunion and has an unpredictable outcome. Our staged approach offers a number of benefits over single-stage reconstruction. First, we wait at least 4 weeks after debridement and soft-tissue coverage before performing the Ilizarov technique of distraction osteogenesis, during which any residual infection may manifest itself before bone reconstruction. Second, it can be used in reconstructing defects of any length and diameter without the need for a bone bank or the risks of donor site morbidity. Third, the quality of bone obtained by distraction osteogenesis is better than that obtained by a vascularized fibular graft.

Disadvantages of the Combined Technique

The combined technique has some disadvantages, including cost of treatment, complexity of added surgery, requirement of multiple outpatient adjustments, and long duration of treatment. The limitations of this study were the small number of enrolled cases, lack of a control group, and short follow-up period. Another limitation was that, in comparing the time from injury to initial surgery among the patients, this cohort of patients was heteronomous because patients were commonly not sent to our hospital immediately.

Conclusion

The combined technique of a perforator artery pedicled neurotrophic flap and distraction osteogenesis should be an effective alternative approach in the salvage treatment of massively traumatized and chronically infected lower extremities.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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References

1. Rollo G, Falzarano G, Ronga M, Bisaccia M, Grubor P, Erasmo R, et al. Challenges in the management of floating knee injuries: results of treatment and outcomes of 224 consecutive cases in 10 years. Injury. 2019;50(Suppl 4):S30–8.
2. Fortina M, Maniscalco P, Carulli C, Meccariello L, Colasanti GB, Carta S. Jockey injuries during the Siena "Palio". A 72-year analysis of the oldest horse race in Italy. Injury. 2019;50(Suppl 4):S56–9.
3. Ronga M, Cherubino M, Corona K, Fagetti A, Bertani B, Valdatta L, et al. Induced membrane technique for the treatment of severe acute tibial bone loss: preliminary experience at medium-term follow-up. Int Orthop. 2019;43:209–15.
4. Gustilo RB, Anderson JT. Prevention of infection in the treatment of one thousand and twenty-five open fractures of long bones: retrospective and prospective analyses. J Bone Joint Surg Am. 2000;58:453–8.
5. Gustilo RB, Mendoza RM, Williams DN. Problems in the management of type III (severe) open fractures: a new classification of type III open fractures. J Trauma. 1984;24:742–6.
6. Saddawi-Konefka D, Kim HM, Chung KC. A systematic review of outcomes and complications of reconstruction and amputation for type IIIB and IIIC fractures of the tibia. Plast Reconstr Surg. 2008;122:1796–805.
7. Cherubino M, Corno M, D'Arpa S, di Summa P, Pellegatta I, Valdatta L, et al. Muscle versus fasciocutaneous flap in lower limb reconstruction: is there a best option? J Reconstr Microsurg. 2017;33:S27–33.
8. Cherubino M, Corno M, Ronga M, Riva G, di Summa PG, Sallam D, et al. The adipo-fascial ALT flap in lower extremities reconstruction Gustillo IIIC-B fractures. An osteogenic inducer? J Invest Surg. 2019;2:1–6.
9. Wang CY, Chai YM, Wen G, Han P. One-stage reconstruction of composite extremity defects with a sural neurocutaneous flap and a vascularized fibular graft: a novel chimeric flap based on the peroneal artery. Plast Reconstr Surg. 2013;132:428e–37e.
10. Lowenberg DW, Feibel RJ, Louie KW, Eshima I. Combined muscle flap and Ilizarov reconstruction for bone and soft tissue defects. Clin Orthop Relat Res. 1996;332:37–51.
11. Chim H, Sontich JK, Kaufman BR. Free tissue transfer with distraction osteogenesis is effective for limb salvage of the infected traumatized lower extremity. Plast Reconstr Surg. 2011;127:2364–72.
12. McKee MD, Yoo DJ, Zdero R, et al. Combined single-stage osseous and soft tissue reconstruction of the tibia with the Ilizarov method and tissue transfer. J Orthop Trauma. 2008;22:183–9.
13. Francel TJ, Vander Kolk CA, Hoopes JE, Manson PN, Yaremchuk MJ. Microvascular soft-tissue transplantation for reconstruction of acute open tibial fractures: timing of coverage and long-term functional results. Plast Reconstr Surg. 1992;89:478; discussion 488–489–87.
14. Lou TF, Hamushan M, Li H, Wang CY, Chai Y, Han P. Staged distraction osteogenesis followed by arthrodesis using internal fixation as a form of surgical treatment for complex conditions of the ankle. Bone Joint J. 2018;100-B(6):755–60.
15. Lou TF, Li H, Chai YM, Wang CY, Liu SH, Hamushan M, et al. Resection arthrodesis using distraction osteogenesis then plating as a hybrid surgical technique for the management of bone sarcomas of the distal tibia. Int Orthop. 2018;42:705–11.
16. Lou TF, Wen G, Wang CY, Chai YM, Han P, Yin XF. L-shaped corticotomy with bone flap sliding in the management of chronic tibial osteomyelitis: surgical technique and clinical results. J Orthop Surg Res. 2019;14:47.
17. Cierny G III, Zorn KE. Segmental tibial defects. Comparing conventional and Ilizarov methodologies. Clin Orthop Relat Res. 1994;301:118–23.
18. Lowenberg DW, Buntic RF, Buncke GM, Parrett BM. Long-term results and costs of muscle flap coverage with Ilizarov bone transport in lower limb salvage. J Orthop Trauma. 2013;27:576–81.
19. Paley D, Catagni MA, Argnani F, Villa A, Benedetti GB, Cattaneo R. Ilizarov treatment of tibial nonunions with bone loss. Clin Orthop Relat Res. 1989;241:146–65.
20. Paley D. Problems, obstacles, and complications of limb lengthening by the Ilizarov technique. Clin Orthop Relat Res. 1990;250:81–104.
21. Cherubino M, Stocco C, Ronga M, Tamborini F, Maggiulli F, di Giovanna D, et al. Comparisons of fascio-cutaneous anterolateral thigh and sandwich fascial ALT free flap in the distal extremity reconstruction. Microsurgery. 2020;40:452–9.
22. Shu H, Ma B, Kan S, Wang H, Shao H, Watson JT. Treatment of posttraumatic equinus deformity and concomitant soft tissue defects of the heel. J Trauma. 2011;71:1699–704.
23. Park S, Lee TJ. Strategic considerations on the configuration of free flaps and their vascular pedicles combined with Ilizarov distraction in the lower extremity. Plast Reconstr Surg. 2000;105:1680–6.
24. Ullmann Y, Fodor L, Ramon Y, Soudry M, Lerner A. The revised "reconstructive ladder" and its applications for high-energy injuries to the extremities. Ann Plast Surg. 2006;56:401–5.
25. 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;20:419–24.
26. Dahl MT, Gulli B, Berg T. Complications of limb lengthening. A learning curve. Clin Orthop Relat Res. 1994;301:10–8.