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Modified Tibial Transverse Bone Transport Technique for Wagner Grade 3-4 Diabetic Foot: Observation of Clinical Outcomes in 117 Cases (Postprint)

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Abstract

Objective To investigate the efficacy of modified tibial transverse transport (TTT) technique: combined bone and periosteal transport in the treatment of patients with Wagner grade 3 and 4 diabetic foot. Methods A retrospective analysis was conducted on the clinical data of 117 diabetic foot patients treated with the modified TTT technique from January 2018 to May 2021. A before-and-after self-control study design was adopted to analyze the postoperative foot preservation rate, functional limb salvage rate, major amputation rate, ulcer healing time, complication rate, improvement of foot skin temperature, rest pain status, and comparison of preoperative and postoperative CTA findings. Results All patients were followed up for 5.5 to 24 months, with a mean follow-up duration of (14.21$±4.06)*months.Thepostoperativefootpreservationrate(noamputationoramputationbelowtheankle)was*
weeks; foot temperature improved significantly postoperatively compared to preoperatively (P<0.01); foot pain in patients with rest pain was significantly relieved (P<0.01); CTA showed that 70.34% (94/117) of patients had improved postoperative vascular conditions, increased microvessel numbers, and reconstruction of the foot vascular network; the complication rate during bone transport was 11.97% (14/117), with incidence rates of skin edge necrosis at the osteotomy site, lower extremity venous thrombosis, and pin tract infection being 5.98% (7/117), 4.27% (5/117), and 1.71% (2/117), respectively. Conclusion The modified TTT technique of combined bone and periosteal transport can promote wound healing by stimulating the reconstruction of lower extremity microcirculation, effectively relieve rest pain symptoms and improve foot temperature in diabetic foot patients in the short term; meanwhile, compared with conventional TTT technique, this method significantly reduces the complication rate and provides an effective treatment modality for diabetic

foot.

Full Text

Abstract

Objective: To investigate the efficacy of modified tibial transverse bone transport (TTT) technology—specifically, combined bone and periosteum transport—in treating patients with Wagner grade 3 and 4 diabetic foot.

Methods: Clinical data from 117 diabetic foot patients treated with modified TTT technology between January 2018 and May 2021 were retrospectively analyzed using a self-controlled before-and-after study design. Outcome measures included postoperative foot preservation rate, functional limb salvage rate, major amputation rate, ulcer healing time, complication rate, improvement in foot skin temperature, resting pain status, and comparison of preoperative and postoperative CT angiography (CTA).

Results: All patients were followed up for 5.5 to 24 months (mean: 14.21 $\pm$ 4.06 months). The postoperative foot preservation rate (non-amputated or below-ankle amputation) was 95.73% (112/117). The functional limb salvage rate (non-amputated or minor amputation distal to the midfoot) was 83.76% (98/117). The major amputation rate (above-ankle amputation) was 4.27% (5/117). Except for amputated patients, all others showed good postoperative ulcer healing with a healing time of 6–14.5 weeks (mean: 9.07 $\pm$ 2.02 weeks). Foot temperature improved significantly postoperatively compared with preoperative values ($P < 0.01$). Resting pain decreased significantly in patients with preoperative pain ($P < 0.01$). CTA showed improved vascular status in 70.34% (94/117) of patients, with increased microvascular density and reconstructed foot vascular networks. The complication rate during bone transport was 11.97% (14/117), comprising skin edge necrosis at the osteotomy site (5.98%, 7/117), lower extremity venous thrombosis (4.27%, 5/117), and pin tract infection (1.71%, 2/117).

Conclusion: Modified TTT technology with combined bone and periosteum transport promotes wound healing by stimulating reconstruction of lower limb microcirculation, effectively relieves resting pain and improves foot temperature in diabetic foot patients in the short term. Compared with traditional TTT technology, this method significantly reduces complication rates, providing an effective treatment modality for diabetic foot.

Keywords: diabetic foot; combined bone and periosteum transport; tibial transverse bone transport

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Introduction

Diabetic foot is a common complication of diabetes mellitus characterized by high morbidity and mortality, posing significant treatment challenges and imposing substantial costs on patients' health. Statistics indicate that approximately 25% of diabetic patients develop foot ulcers during their lifetime. The International Diabetes Federation reports that 9.1–26.1 million diabetic patients develop diabetic foot ulcers annually, with one-fifth requiring amputation—primarily among those with Wagner grade $ $3 lesions. Worldwide, one patient undergoes diabetes-related amputation every 30 seconds. In developed countries, diabetes accounts for over 60% of below-knee amputations. Furthermore, approximately 50% of patients who undergo major amputation will require re-amputation within five years, with a 5-year mortality rate of 25–50% after amputation [1-4].

Current treatment modalities for diabetic foot are diverse and typically require multidisciplinary comprehensive management. Despite guideline recommendations, treatment remains non-uniform, focusing primarily on improving local circulation, promoting wound healing, and controlling infection [5], with adjunctive techniques including debridement, negative pressure wound therapy, antibiotic-loaded bone cement, hyperbaric oxygen, ozone therapy, and endovascular intervention [6-11]. However, outcomes remain limited, necessitating additional therapeutic technologies to promote diabetic foot ulcer healing and improve limb salvage rates.

Tibial transverse bone transport (TTT) is a technique developed based on the tension-stress principle proposed by Russian orthopedic surgeon Ilizarov [12]. By distracting a tibial bone segment, TTT stimulates reconstruction of lower limb microcirculation [13], thereby alleviating pain, improving foot temperature, and promoting ulcer healing. However, traditional TTT technology involves a large incision with a single large bone segment, resulting in numerous complications including skin edge necrosis, iatrogenic fracture, necrosis and detachment of the transported bone segment, and delayed ambulation, with relatively high incidence rates.

Our research team modified the traditional TTT technique by preserving and suturing the periosteum, employing a combined bone and periosteum transport approach. In this study, we observed and analyzed 117 diabetic foot patients treated with this modified technique, which effectively reduced the aforementioned complications. The results are reported below.

1.1 Case Inclusion and Exclusion Criteria

Inclusion criteria: (1) Diabetic foot patients with Wagner stage 3 or 4 lesions; (2) Ambulatory capacity; (3) No severe cardiopulmonary or renal dysfunction; (4) No severe coagulation disorders; (5) At least one patent infrapopliteal main vessel extending to the ankle joint with vascular patency $ $70% and forming a vascular network.

Exclusion criteria: (1) Patients with psychiatric disorders unable to cooperate with treatment; (2) Patients with other uncontrolled severe complications, such as uncontrolled systemic or deep infection; (3) Patients unable to tolerate anesthesia due to cardiovascular complications or renal failure, or those with severe underlying diseases precluding surgical tolerance; (4) Patients with superficial femoral or popliteal artery occlusion, or absence of arterial branches (anterior tibial, posterior tibial, or peroneal arteries) supplying the lower leg; (5) Patients with incomplete clinical data.

1.2 General Patient Characteristics

This cohort comprised 80 males and 37 females, aged 56–82 years (mean: 65.9 years). Diabetes duration ranged from 2 to 43 years (mean: 14.9 years), and diabetic foot duration ranged from 1 to 24 months (mean: 8.2 months). Wagner staging: 48 patients with stage 3 and 69 with stage 4 lesions. Thirty-five patients presented with resting pain.

1.3 Preoperative Management

Comprehensive preoperative evaluations were completed, with measures to improve circulation, provide nutritional support to nerves, and strictly control blood glucose. The following standards were required: (1) Fasting blood glucose $ $8 mmol/L and 2-hour postprandial glucose $ $12 mmol/L; (2) Correction of nutritional status with albumin >30 g/L, and correction of internal environment imbalances, particularly latent electrolyte disturbances and pleural effusion; (3) Infection control with antibiotics to localize foot infection and prevent "chain infection"; (4) Thorough foot debridement with removal of infected and necrotic tissue; (5) Preoperative foot temperature measurement and pain assessment for all patients.

1.4 Surgical Technique

Peripheral nerve block anesthesia was selected without tourniquet application to avoid exacerbating lower limb circulatory impairment. A six-step preoperative assessment and surgical protocol was employed.

The medial aspect of the proximal to middle third of the tibia was selected as the osteotomy site. Skin tension and laxity were assessed, the traction device was pre-positioned on the body surface, and drilling locations were selected.

Step 1: Site selection and assessment: At the predetermined traction rod placement site, a 2.7-mm diameter drill bit was used to penetrate unilateral cortical bone perpendicular to the bone surface until reaching the medullary cavity. Observable bleeding from the medullary cavity indicated adequate blood supply [Figure 1: see original paper].

Step 2: Incision design and periosteal protection: Based on the distance between the two traction rods, two precise holes were drilled using a 2.7-mm diameter drill bit. A 2-cm curved incision was made along these holes with subcutaneous dissection and meticulous periosteal preservation [Figure 2: see original paper].

Step 3: Drill orientation and osteotomy method: The osteotomy block size was designed according to the required tibial surface area, typically selecting a boundary 5 mm from the tibial crest. Drill orientation should be perpendicular to the medullary cavity surface to avoid penetrating both cortices. Generally, a square or rectangular block measuring (2–2.5) × (2–2.5) cm^2 was designed [Figure 3: see original paper].

Step 4: Periosteal preservation and osteotomy technique: The periosteum over the drilling site was first incised with a No. 15 blade and retracted approximately 2 mm on both sides to expose the bone holes. An ultrathin osteotome was used to create a mobile bone flap, and the periosteum was sutured with 5-0 absorbable sutures [Figure 4: see original paper].

Step 5: Percutaneous fixation of traction rods [Figure 5: see original paper].

Step 6: External fixator placement and skin closure: After external fixator placement, the skin was closed with interrupted sutures. Finally, the incision was disinfected with 75% ethanol and dressed [Figure 6: see original paper].

1.5 Postoperative Management

Postoperative measures included infection prophylaxis, blood glucose monitoring and strict control (fasting glucose $ $8 mmol/L, 2-hour postprandial glucose $ $12 mmol/L), daily pin tract cleaning and disinfection, and daily dressing changes. Patients were encouraged to ambulate beginning one week postoperatively. Transverse bone transport was initiated at 12–14 days postoperatively at a rate of 1 mm/day, divided into four sessions. After 10 mm of distraction, radiographs were obtained to confirm bone fragment position. Following a 3-day interval, the segment was retracted 2 mm at the same speed and method. Radiographs were repeated to confirm and adjust bone fragment position, followed by outward distraction to 15 mm. After radiographic confirmation, the segment was returned to its original position after 3 days. The external fixator was removed after initial healing of the bone window.

1.6 Evaluation Indicators

1. Postoperative foot preservation rate (non-amputated or below-ankle amputation/toe amputation), functional limb salvage rate (non-amputated or minor amputation distal to the midfoot), and major amputation rate (above-ankle amputation).
2. Ulcer healing time.
3. Complication rate.

4. Foot skin temperature improvement: Measured at the midpoint of the dorsal foot using an infrared thermometer. Measurements were taken at three time points (morning, noon, evening) and averaged. Patients wore socks for at least 2 hours before measurement. Assessments were performed at 1, 2, 4, and 8 weeks postoperatively.
5. Resting pain status: Assessed using the Visual Analogue Scale (VAS) at 1, 2, 4, and 8 weeks postoperatively.
6. Comparison of preoperative and postoperative CTA to evaluate vascular recanalization and network reconstruction.

Results

Among the 117 patients, the foot preservation rate was 95.73% (112/117) and the functional limb salvage rate was 83.76% (98/117). Five patients ultimately underwent above-ankle amputation (major amputation) due to severe infection or complications, including four below-knee and one above-knee amputation, yielding a major amputation rate of 4.27% (5/117). No proximal migration of amputation levels was observed during follow-up. Except for amputated patients, all others demonstrated good ulcer healing (typical cases shown in [Figure 9: see original paper]-[Figure 11: see original paper]) with healing times of 6-14.5 weeks (mean: 9.07 ± 2.02 weeks). No ulcer recurrence was observed during follow-up, and all amputation wounds achieved primary healing.

Foot temperature improved significantly postoperatively compared with preoperative values ($P < 0.01$), with the most pronounced improvement occurring during the first two weeks ($P > 0.05$ between weeks 1 and 2) [Figure 7: see original paper]. Patients with preoperative resting pain experienced significant pain relief postoperatively ($P < 0.01$). VAS scores decreased markedly beginning at week 1, with pain substantially resolved by week 2 (no significant difference between weeks 2 and 4, $P > 0.05$), though scores increased slightly by week 8 [Figure 8: see original paper].

CTA demonstrated improved vascular status in 70.34% (94/117) of patients on the transport side, with increased microvascular density and establishment of collateral circulation (typical cases shown in [Figure 14: see original paper]-[Figure 15: see original paper]).

Fourteen patients experienced postoperative complications (11.97% incidence). The most common complication was skin edge necrosis at the osteotomy site (7 patients, 5.98%), followed by lower extremity venous thrombosis (5 patients, 4.27%). Two patients developed infection during transport, yielding a pin tract infection rate of 1.71% (2/117).

3.1 TTT Promotes Collateral Circulation Establishment and Short-Term Improvement in Foot Temperature and Pain Relief

The primary factor impeding diabetic foot ulcer healing is lower limb circulatory impairment [14]. Our retrospective analysis of 432 patients with Wagner grade 3 and 4 diabetic foot revealed that approximately two-thirds had lower limb circulatory disturbances, with prevalence positively correlated with age and disease duration. Therefore, effectively improving lower limb arterial patency and foot tissue perfusion to reconstruct occluded blood flow is critical for treating diabetic foot ulcers and represents the decisive factor for limb salvage [15].

Currently, endovascular intervention is the mainstream technology for improving lower limb ischemia, with definitive effects. However, this treatment only restores macro-arterial blood flow with suboptimal effects on foot microcirculatory perfusion. Additionally, it presents numerous challenges including prolonged radiation exposure for medical staff, high costs, short duration of maintained circulation, incisional liquefaction necrosis, and requirement for long-term medication [16].

TTT technology, an innovative lower limb microcirculation reconstruction technique independently developed by Chinese scholars, has attracted widespread clinical attention due to its lower cost and relatively simple, minimally invasive surgical procedure. Its proposed mechanisms include induction of lower limb microvascular network regeneration, tibial fenestration decompression, and mobilization of stem cell migration to the foot for reconstruction [17,18].

Foot temperature is the most intuitive objective manifestation of lower limb circulation, and early monitoring facilitates prevention of foot ulcers and gangrene [19]. Clinical observations have demonstrated that when wound bed temperature falls below core body temperature, activities of late inflammatory cells and fibroblasts are impeded, resulting in delayed healing [20]. In vitro experiments have shown that the critical temperature for neutrophils, fibroblasts, and epithelial cells is 33°C; below this threshold, cellular viability decreases substantially [21]. Our diabetic foot center's retrospective analysis of large case series revealed that when toe temperature falls below 34°C, wounds rarely heal through conventional means and typically require interventional or other surgical interventions to increase local temperature before healing can occur.

This study used a Beurer infrared thermometer for measurements at multiple preoperative and postoperative time points. The most significant improvement occurred during the first two weeks, with gradually diminishing effects thereafter, demonstrating that TTT technology can promote lower limb circulation and achieve satisfactory short-term foot temperature improvement.

Pain relief represents another major advantage of TTT technology. The vast majority of patients experience varying degrees of resting pain relief after surgery, similar to the effects of endovascular treatment and another manifestation of improved limb temperature. This study employed the VAS scoring system, which is widely used for diabetic foot pain assessment [22]. Results showed pain relief beginning at postoperative week 1, with optimal effects at weeks 2 and 4. However, some patients experienced pain recurrence after week 8, suggesting that TTT provides effective short-term resting pain relief directly related to tibial fenestration decompression and relief of vascular spasm. Combined with oral microcirculation-improving medications and foot functional exercise, excellent long-term pain relief can be achieved.

3.2 TTT Improves Functional Limb Salvage Rate

Functional limb salvage is the core objective of diabetic foot management, and foot wound healing efficiency is a crucial indicator for evaluating surgical efficacy. Review of our previous large case series revealed that amputation rates exceeded 70% in Wagner grade 3 and 4 diabetic foot patients. These patients represent the primary population for limb salvage efforts. Although necrotic and infected tissues in such patients are difficult to preserve, TTT technology maximizes limb preservation, enabling ambulation without prostheses or braces—true functional limb salvage.

In this cohort, 98 patients achieved functional limb salvage (non-amputated or amputation distal to the midfoot), yielding a functional salvage rate of 83.76%. Fourteen patients underwent below-ankle amputation proximal to the midfoot; for these patients, we generally recommend postoperative foot brace assistance for ambulation. Although not classified as functional limb salvage, the overall foot preservation rate reached 95.73% (112/117). Five patients required major amputation and eventual prosthetic fitting. Except for amputated patients, all others achieved ulcer healing with a mean healing time of (9.07 ± 2.02) weeks, representing higher wound healing efficiency compared with previous case series [23,24].

3.3 Modified TTT Significantly Reduces Postoperative Complications

While TTT technology demonstrates definitive efficacy in diabetic foot salvage, its therapeutic outcomes and complication rates relate closely to technical details and perioperative care. Without profound understanding of Ilizarov principles and extensive practical experience with diabetic foot cases, this technique carries high complication rates with severe consequences, including anterior tibial skin necrosis, detached necrotic transport bone segments, deep venous thrombosis with pulmonary embolism, pin tract infection, and tibial fracture. Management of these complications is often extremely challenging. Therefore, optimizing TTT operative technique and evaluating surgical efficacy are urgently needed.

This study employed modified TTT technology—combined bone and periosteum transport—which demonstrated significantly reduced complications and notable advantages compared with previous studies [25-27]. The modified technique preserves and sutures the periosteum, effectively stabilizing traction rods and preventing bone segment deviation or retraction displacement while reducing local medullary cavity bleeding and soft tissue irritation that causes skin edge necrosis. In this series, only 7 patients developed postoperative skin edge necrosis at the osteotomy site, all of whom ultimately discontinued transport.

To prevent skin edge necrosis, surgical technique should avoid excessive skin traction at the incision site, and postoperative monitoring should promptly adjust transport speed when excessive local tension or skin color changes are observed. Lower extremity venous thrombosis primarily results from large surgical wounds, immobility due to pain or fear of fixator displacement, and prolonged bed rest in traditional TTT. The modified TTT employs a "double-small-block" osteotomy configuration determined by tibial transverse diameter, with oblique osteotomy relative to the tibial surface to effectively prevent iatrogenic fracture and enable early ambulation, thereby reducing venous thrombosis. In this study, most patients ambulated within one week postoperatively, yielding a venous thrombosis rate of 4.27%, substantially lower than previous reports.

Pin tract infection primarily results from delayed wound healing, rapid bacterial proliferation, and inadequate pin tract care. Previous literature reports widely varying infection rates of 10–89% [28-31]. This series had only 2 cases of mild pin tract infection (1.71% incidence), attributed to good glycemic control, shorter external fixation duration, and rigorous postoperative care. Both patients achieved infection control through pin tract cleaning and regular dressing changes. The primary cause of bone segment detachment is malpositioning during free bone flap creation, resulting in deviation during traction and inability to reposition effectively, leading to malunion or nonunion. Periosteal suturing fixation in this study substantially reduced this complication, with no bone segment detachment observed among the 117 patients.

4. Summary

Key operative principles of modified TTT technology (combined bone and periosteum transport) include:

1. **Patient selection:** In addition to CTA-based criteria for lower limb blood supply, preoperative bone drilling at the proximal to middle tibia is performed. Flowing medullary blood indicates adequate blood supply and predicts good transport outcomes. In previous cases, absence of significant medullary bleeding suggested abundant yellow marrow with insufficient medullary blood supply and stem cells at the transport site, resulting in suboptimal TTT outcomes.
2. **Bone segment sizing:** The anteromedial tibial transverse diameter serves as the primary reference. Drilling and osteotomy are performed obliquely toward the medullary cavity within 0.5 cm of both tibial crests [FIGURE:12, FIGURE:13], without penetrating both cortices. This

reduces surgical trauma and recovery time, facilitates early ambulation, and decreases deep venous thrombosis risk.

3. **Periosteal preservation and suturing:** The periosteum along all four osteotomy edges is sequentially incised. After creating each osteotomy edge, the periosteum is sutured with 5-0 PDS sutures. This stabilizes the transport bone segment with traction rods at its original tibial position [Figure 5: see original paper], effectively preventing displacement, non-reduction, and sequestrum formation.
4. **Postoperative hemostasis and early ambulation:** Adequate hemostasis with drain placement and encouragement of early ambulation effectively prevent skin edge infection/necrosis and deep venous thrombosis.

However, this study has limitations: (1) It employed only a self-controlled before-and-after design without a control group, necessitating future large-sample randomized controlled studies; (2) Since most patients had the external fixator removed at approximately two months after wound healing, long-term data on foot temperature and resting pain are lacking and require further investigation; (3) Although TTT technology can regenerate the lower limb microcirculatory system and reconstruct foot blood supply to facilitate wound healing, the regenerated vessels remain in abnormal blood, and the reconstructed microvasculature is unstable, creating potential for diabetic foot recurrence. Since this technique is only effective for microcirculation reconstruction, patients with combined large- and medium-artery occlusion may benefit from initial endovascular treatment followed by TTT [32], potentially yielding better medium- to long-term outcomes.

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