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Clinical study on double bone flap traction-modified tibial transverse transport in the treatment of diabetic foot ulcers

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Abstract: Objective To investigate the efficacy of the double bone flap traction-modified tibial transverse transport (TTT) in the treatment of diabetic foot ulcers (DFU), and its impact on the ankle-brachial index (ABI), skin temperature, and Visual Analogue Scale (VAS) score of the affected limb. **Methods** A retrospective selection was made of 38 DFU patients admitted to the Department of Hand Microvascular Surgery of Dongguan People's Hospital from January 2022 to October 2024. According to the surgical method, they were divided into three groups: Group A ($n=10$, undergoing double bone flap traction modified TTT), Group B ($n=8$, undergoing traditional TTT), and Group C ($n=20$, undergoing conventional debridement and wound revision). The ABI, skin temperature, and VAS score of the affected limb were compared among the three groups before surgery, one week after surgery, and one month after surgery. The marked improvement rate after 3 months of treatment, the healing time of small wounds, and the recurrence rate within six months after healing of small wounds were also compared. **Results** After surgery, Group A showed significant short-term improvement in ABI, skin temperature, and VAS score of the affected limb, and these parameters were significantly better than those in Groups B and C at one month postoperatively ($P<0.05$). The follow-up period ranged from 6 to 15 months. During follow-up, there was a statistically significant difference in the marked improvement rate after 3 months of treatment among Groups A, B, and C [100.0% (10/10), 75.0% (6/8), 40.0% (8/20), $\chi^2=10.925$, $P=0.004$]. There was also a statistically significant difference in the healing time of small wounds among Groups A, B, and C [(2.9 ± 0.7)months, (4.1 ± 1.0)months, (4.3 ± 0.8)months, $F=10.035$, $P=0.004$]. **Conclusion** The double bone flap traction-modified TTT can significantly improve the microcirculation of the affected limb and shorten wound healing time, and its efficacy is significantly superior to that of traditional TTT and conventional debridement and wound enlargement.

Keywords: Double bone flap traction; Tibial transverse transport; Diabetic foot; Distraction osteogenesis; Regeneration

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The prevalence of diabetes in China is increasing year by year, reaching 12.4% in 2019 [1-2]. Fifteen percent of these patients are complicated with diabetic foot, and 85% of them present with diabetic foot ulcers (DFU) as the initial manifestation. DFU is characterized by persistent non-healing and high treatment difficulty, with an amputation rate exceeding 30% [3-4]. Vascular and neuropathic lesions below the ankle joint are the leading causes of DFU.

Current clinical treatments for DFU still rely on surgical interventions such as debridement, extensive debridement, continuous negative pressure wound therapy, and revascularization interventions. However, debridement, extensive debridement and continuous negative pressure wound therapy mainly target the wound surface and cannot fundamentally improve the circulation of the affected limb, resulting in unsatisfactory therapeutic effects [5]. Vascular interventional therapy has obvious technical limitations in the traditional application around the ankle joint. In particular, the recanalization rate of blood vessels with a diameter of less than 2 mm is low, while the restenosis rate is high, which severely restricts its clinical application [6].

In recent years, tibial transverse transport (TTT) has achieved satisfactory outcomes in the treatment of DFU in China. Its core technical principle is the tension-stress law: when biological tissues are stretched, certain tension is generated, which can stimulate tissue regeneration and sustained growth, thereby forming a rich capillary network and accelerating wound healing [7-12]. TTT is mainly indicated for Wagner grade 2-4 DFU patients without large-vessel occlusion of the lower extremities, or those with recanalized occlusion via interventional procedures. With the widespread application of TTT, its limitations have gradually emerged. After the bone fragment is distracted and repositioned, the stimulation from periosteal stretching ceases [13], and the promoting effect on capillary proliferation disappears, limiting wound healing. In addition, after the transport of large bone fragments, complications such as necrosis of the skin edge at the transport site and avascular necrosis of the distracted bone fragment may occur [14].

To address the limitations of conventional TTT, our research team has improved the bone flap design, optimized the structure of the external fixator, and adjusted

the bone transport mode. These modifications enable sustained stretching stimulation of the periosteum, maintain the driving factors for capillary regeneration, and effectively enhance the clinical efficacy of DFU treatment.

1 Materials and Methods

1.1 General Data

A total of 38 patients with DFU and imaging-confirmed lower extremity arterial disease, admitted to the Department of Hand Surgery, Dongguan People's Hospital from January 2022 to October 2024, were enrolled in this study. Inclusion criteria: (1) Patients with long-standing (disease duration > 3 months) Wagner grade 3-4 DFU; (2) Lower extremity arterial occlusion, but at least one artery below the knee extends to the ankle, or revascularization to the ankle is achieved after interventional therapy; (3) Clear surgical intention and tolerance to surgery. Exclusion criteria: (1) Poor compliance, unable to cooperate with treatment; (2) Severe coagulation dysfunction; (3) Vascular occlusion above the knee with no arterial branches supplying the lower leg; (4) Severe complications of other systemic diseases, intolerant to anesthesia and surgery. This study was approved by the Medical Ethics Committee of Dongguan People's Hospital (Ethics Approval No.: KYKT2021-061). All patients provided written informed consent prior to participation.

Patients were divided into three groups according to the surgical procedure. Group A ($n=10$) was treated with dual-bone flap traction modified TTT. Group B ($n=8$) was treated with conventional TTT. Group C ($n=20$) underwent routine debridement and extensive debridement. There were no statistically significant differences in gender, age, or Wagner classification among the three groups ($P>0.05$), indicating comparability between groups (Table 1).

1.2 Preoperative Preparation and Surgical Instruments

Preoperatively, color Doppler ultrasound of bilateral lower extremity arteries and computed tomography angiography (CTA) were performed. Blood glucose was strictly controlled, with target levels of fasting blood glucose < 8 mmol/L and postprandial blood glucose < 12 mmol/L. Hypoalbuminemia and electrolyte disturbances were corrected. The ankle-brachial index (ABI), skin temperature of the affected limb, wound area, wound depth, and visual analogue scale (VAS) score were measured and recorded in all patients before surgery. The bone transport external fixators included the Dabo tibial transport frame (Xiamen Dabo Medical Devices Co., Ltd., Product No.: 109970200) and the modified tibial transport frame (Figure 1). Based on the standard Dabo tibial transport frame, the modified fixator was designed with two sets of independently rotatable buttons on the original transport base, enabling separate distraction of two small bone fragments.

1.3 Surgical Procedures and Postoperative Management

1.3.1 Group A

An approximately 5 cm curved incision was made medially at the middle and distal tibia (about 5 cm distal to the tibial tuberosity). The skin, subcutaneous tissue, and fascia were incised to define the osteotomy range of the tibia, with an osteotomy length of approximately 5 cm and width of approximately 1.5 cm. The tibia was exposed, with the periosteum preserved. The tibial cortex was incised bilaterally within the planned osteotomy range to form a mobile bone flap, which was then bisected into two bone flaps measuring 2.5 cm × 1.5 cm. One traction pin was inserted superiorly and inferiorly to each bone flap. Two steel pins for the external fixator were inserted parallelly into the proximal and distal tibia, respectively. The external fixator was installed, followed by the attachment of a movable transverse distractor to the external fixator (Figure 2). Postoperative management: Anteroposterior and lateral radiographs of the affected tibia were obtained on postoperative day 5. Transverse distraction of the two tibial bone windows was initiated slowly based on the local wound condition, at a daily rate of 1 mm divided into 6 sessions, and discontinued after 11 days. After repeated radiographs, reverse distraction of the two tibial bone windows was performed at a daily rate of 1 mm divided into 6 sessions. After 8 days, distraction of the superior bone flap was terminated, while the inferior bone flap continued downward distraction for an additional 11 days. The distal tibial bone window was then repositioned. The bone transport device was removed 5 days after bone flap repositioning. Partial weight bearing was permitted with the assistance of a walker. Relevant indicators were regularly observed and recorded during the bone transport period per the study protocol.

1.3.2 Group B

The same exposure and osteotomy techniques as Group A were employed. However, the bone flap was not bisected in Group B; instead, conventional single large bone flap transport was performed, and a standard bone transport frame was installed using the method described for Group A. Postoperative management: Routine postoperative care was identical to that of Group A. Anteroposterior and lateral radiographs of the affected tibia were obtained on postoperative day 5. Transverse distraction of the tibial bone window was initiated slowly based on the local wound condition, at a daily rate of 1 mm divided into 6 sessions, and discontinued after 11 days. After repeated radiographs, reverse distraction of the tibial bone window was performed at a daily rate of 1 mm divided into 6 sessions for 11 days, followed by repositioning of the tibial bone window. Radiographs were obtained 1 month postoperatively. The bone transport device was removed according to bone healing status, and partial weight bearing with a walker was allowed, with precautions taken to prevent falls. Relevant indicators were regularly observed and recorded during the bone transport period per the study protocol.

1.3.3 Group C

A lower extremity tourniquet was not used intraoperatively to facilitate intraoperative assessment of tissue viability. Viable tissue was preserved as much as possible, while necrotic, infected tissue and inflammatory granulation tissue were completely removed. Sinuses were fully opened to ensure adequate drainage. Debridement

depth was controlled until fresh bleeding was observed from the wound surface. Postoperative management: Surgical wound debridement and dressing changes were performed every other day postoperatively. Relevant indicators were regularly observed and recorded per the study protocol.

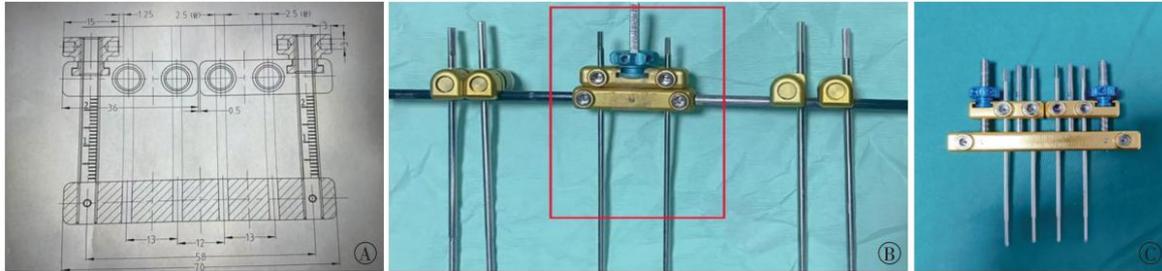


Fig.1 Improved design and finished product of bone mover seat



Note: A shows the preoperative body surface localization and marking; B shows the incision design; C shows the completed installation of the bone transport frame in accordance with the surgical procedures; D shows the operative field appearance on the 11th day of bone transport, with the two bone flaps separated from the tibia by 11 mm; E shows the X-ray film on the 11th day of bone transport, demonstrating the two bone flaps separated from the tibia by 11 mm; F shows the X-ray film after completion of bone transport and removal of the external fixator, revealing that the proximal tibial bone flap is 3 mm higher than the distal one.

Fig.2 Improved TTT process, postoperative wound condition, and postoperative imaging finding

Tab.1 Comparison of general data among three groups

Item	Group A (n=10)	Group B (n=8)	Group C (n=20)	χ^2/F value	P value
Gender [case (%)]				1.070	0.586
Male	8 (80.0)	5 (62.5)	16 (80.0)		
Female	2 (20.0)	3 (37.5)	4 (20.0)		
Age (years, $\bar{x} \pm s$)	71.1±7.3	66.0±11.2	63.9±9.5	1.972	0.154
Wagner Grade [case (%)]				0.095	0.954
Grade 3	2 (20.0)	2 (25.0)	4 (20.0)		
Grade 4	8 (80.0)	6 (75.0)	16 (80.0)		

1.4 Outcome Measures

(1) ABI: The systolic blood pressures of the affected

ankle and the upper arm were measured separately, and the ABI was calculated [15-17]. (2) Affected limb skin temperature: An infrared thermometer was used to measure the skin temperature of the area distal to the ankle joint of the affected limb. At least 3 sites including the toe tips were monitored, and the average value was recorded [15-17]. (3) VAS score: The VAS score of the affected limb was documented based on the patient's subjective pain perception [15-17]. (4) Marked effective rate at 3 months post-treatment: The therapeutic efficacy was evaluated mainly with reference to the Texas Classification [18]. A marked effect was defined as a 2-grade reduction in lesion severity and a reduction in ulcer area by more than two-thirds [6]. (5) Healing time of small wounds: Healing was defined as complete epithelization of the ulcer surface, no obvious scar contracture or dysfunction, favorable local blood circulation, and glossy skin. Given that wound size and depth influence healing time, this study only recorded

the healing time of wounds with Wagner grade 4 and an ulcer area < 5 cm². (6) Recurrence rate within 6 months after small wound healing: The recurrence rate within 6 months after wound healing in each group was calculated during the follow-up period.

1.5 Statistical Methods

Statistical analysis was performed using SPSS 26.0 software. Normally distributed measurement data were expressed as $\bar{x}\pm s$. One-way analysis of variance was used for comparisons among three groups, and the SNK-*q* test was used for pairwise comparisons. Repeated-measures ANOVA was applied for comparisons at multiple time points. Enumeration data were presented as cases (%), and the χ^2 test was used for intergroup comparisons. A two-sided test with a significance level of $\alpha = 0.05$ was adopted.

2 Results

2.1 Comparison of ABI Among the Three Groups

There was a significant interaction effect of time and group on ABI in the three groups ($P<0.01$). No statistically significant difference in ABI was observed among the three groups 1 day preoperatively ($F=1.121, P=0.337$). In Group A, ABI was significantly improved at 1 week and 1 month postoperatively compared with 1 day preoperatively ($P<0.05$). In contrast, ABI in Groups B and C showed an initial increase followed by a decrease, with statistically significant differences ($P<0.01$) (Table 2).

2.2 Changes in Skin Temperature of the Affected Limb

A significant interaction effect of time and group on the skin temperature of the affected limb was detected in the three groups ($P<0.01$). There was no statistically significant difference in skin temperature among the three groups 1 day preoperatively ($F=0.580, P=0.565$). At 1 week postoperatively, the skin temperature of the affected limb in all three groups was significantly higher than the preoperative baseline, and that in Group B was significantly lower than in Groups A and C ($P<0.05$). The skin temperature of the affected limb in Group A remained elevated compared with the preoperative level, with no statistically significant difference between 1 week and 1 month postoperatively ($P>0.05$). At 1 month postoperatively, the skin temperature in Group C was lower than that at 1 week postoperatively ($P<0.05$) and significantly lower than that in Group A ($P<0.05$) (Table 3).

2.3 Comparison of VAS Scores

A significant interaction effect of time and group on VAS scores was found in the three groups ($P<0.01$). No statistically significant difference in VAS scores was noted among the three groups 1 day preoperatively ($F=0.108, P=0.898$). In Group A, VAS scores were significantly

reduced at both 1 week and 1 month postoperatively ($P<0.05$). In Groups B and C, VAS scores decreased initially but increased subsequently, with no sustained therapeutic effect ($P<0.05$). At 1 month postoperatively, the VAS score in Group A was significantly lower than those in Groups B and C ($P<0.05$) (Table 4).

2.4 Comparison of Wound Healing Outcomes

There was a statistically significant difference in the marked effective rate among the three groups at 3 months post-treatment ($P<0.01$). The marked effective rate in Group A was significantly higher than that in Group C ($P<0.05$), while no statistically significant differences were found between Group B and Groups A or C ($P>0.05$). The healing time of small wounds in Group A was significantly shorter than that in Groups B and C ($P<0.05$), with no statistically significant difference between Groups B and C ($P>0.05$). No statistically significant difference in the recurrence rate within 6 months after small wound healing was observed among the three groups ($P>0.05$) (Table 5).

Tab.2 Comparison of ABI among three groups before and after surgery ($\bar{x}\pm s$)

Group	1 day before surgery	1 week after surgery	1 month after surgery
Group A(n=10)	0.48±0.09	0.68±0.08 ^a	0.70±0.10 ^a
Group B(n=8)	0.46±0.13	0.61±0.16 ^a	0.57±0.19
Group C(n=20)	0.52±0.10	0.74±0.13 ^{ab}	0.54±0.13 ^{cd}
F/P _{group} value	7.893/0.001		
F/P _{time} value	144.672/<0.001		
F/P _{interaction} value	2.981/0.019		

Note: compared with the value at 1 day before surgery in the same group, ^a $P<0.05$; compared with Group B, ^b $P<0.05$; compared with the value at 1 week after surgery in the same group, ^c $P<0.05$; compared with Group A, ^d $P<0.05$.

Tab.3 Comparison of the affected limb temperature among three groups before and after surgery (°C, $\bar{x}\pm s$)

Group	1 day before surgery	1 week after surgery	1 month after surgery
Group A(n=10)	27.00±3.09	33.50±2.47 ^a	32.90±2.43 ^a
Group B(n=8)	27.90±3.00	31.60±3.95 ^a	29.00±3.50
Group C(n=20)	28.10±2.29	35.20±3.12 ^{ab}	30.00±4.17 ^{cd}
F/P _{group} value	4.256/0.019		
F/P _{time} value	87.534/<0.001		
F/P _{interaction} value	3.894/0.003		

Note: compared with the value at 1 day before surgery in the same group, ^a $P<0.05$; compared with Group B, ^b $P<0.05$; compared with the value at 1 week after surgery in the same group, ^c $P<0.05$; compared with Group A, ^d $P<0.05$.

Tab.4 Comparison of VAS score among three groups before and after surgery (point, $\bar{x}\pm s$)

Group	1 day before surgery	1 week after surgery	1 month after surgery
Group A(n=10)	6.80±1.48	2.10±0.74 ^a	1.80±0.92 ^a
Group B(n=8)	7.10±1.36	3.50±0.76 ^{ab}	4.10±1.73 ^a
Group C(n=20)	6.90±1.33	3.80±1.44 ^{ab}	4.80±1.76 ^a
F/P _{group} value	5.782/0.005		
F/P _{time} value	213.459/<0.001		
F/P _{interaction} value	4.127/0.002		

Note: compared with the value at 1 day before surgery in the same group, ^a $P<0.05$; compared with Group A, ^b $P<0.05$.

Tab.5 Comparison of wound healing among three groups

Group	Marked effective rate at 3 months post-treatment (%)	Healing time of small wounds (months, $\bar{x}\pm s$)	Recurrence rate within 6 months after small wound healing (%)
Group A (n=10)	100.0	2.9±0.7	10.0
Group B (n=8)	75.0	4.1±1.0 ^a	25.0
Group C (n=20)	40.0 ^a	4.3±0.8 ^a	40.0
χ^2/F value	10.925	10.035	2.994
P value	0.004	0.004	0.224

2.5 Typical Case

A 72-year-old male patient was admitted with a 1-month history of ulceration on the left foot. The admission diagnosis was type 2 diabetes mellitus with left diabetic foot (Wagner grade 4). The patient received modified left tibial TTT and recovered well postoperatively (Figure 3). Preoperative ABI of this patient was 0.51, which increased to 0.72 at 1 week postoperatively and 0.79 at 1 month postoperatively. The preoperative skin temperature of the affected limb was 29.5 °C, rising to 37.3 °C at 1 week postoperatively and 36.1 °C at 1 month postoperatively. The preoperative VAS score was 5, which decreased to 1 at both 1 week and 1 month postoperatively.



Note: A shows the preoperative ulcer of the left foot, with dry necrosis of partial toe tissue and ulceration extending to the bone; B shows the grossly visible tissue proliferation of the plantar wound 1 week after modified TTT treatment; C shows the follow-up at 2 months postoperatively, with the hallux wound mostly closed and only a mung bean-sized granular wound remaining on the plantar surface, without inflammatory manifestations; D shows the follow-up at 3 months postoperatively, with both the hallux and plantar wounds healed with scar formation, no bleeding or exudation, and the toe tip showing a reddish color with good blood supply; E shows the preoperative lower extremity CTA, revealing an indistinct vascular network in the left foot; F shows the follow-up lower extremity CTA at 2 months postoperatively, demonstrating a significantly richer vascular network in the left foot compared with the preoperative state.

Fig.3 The process of wound healing in a DFU patient undergoing modified TTT

3 Discussion

This clinical case analysis preliminarily confirms the feasibility and efficacy of modified TTT in the treatment of DFU. This modified procedure exhibits significant advantages in relieving lower extremity pain, improving peripheral microcirculation, and promoting wound healing, demonstrating promising clinical application prospects.

The core pathological mechanism of DFU lies in peripheral vascular disease and microcirculatory disturbance, leading to frequently unsatisfactory outcomes with conventional treatments. Improving lower extremity microcirculation is the foundation for promoting DFU healing. Currently, vascular interventional therapy is the mainstream approach to improve lower extremity circulation, effectively recanalizing large and medium arteries and enhancing blood supply to the affected foot in the short term. However, it has limitations: it fails to treat small and arterioles, and has a high incidence of postoperative vascular restenosis or occlusion,

resulting in limited overall improvement of microcirculation. TTT is a well-established technique for DFU treatment that effectively improves lower extremity microcirculation. Established in animal experiments by Professor Ilizarov in 1989, the technique was first successfully applied clinically for the treatment of lower extremity ischemic diseases by Professor Qu Long in 2000. In 2019, Professor Hua Qikai's team further optimized the protocol for DFU treatment and achieved satisfactory clinical outcomes [9].

With the widespread clinical application of TTT, complications of the conventional procedure have gradually emerged: a large surgical incision (usually 10–15 cm); stress concentration on local soft tissues caused by distraction of a single bone fragment, which predisposes to blood supply disturbance and tissue necrosis; a long transport period delaying ambulation; a prolonged bone fragment repositioning time increasing the risk of iatrogenic fracture; and the loss of sustained stretching stimulation after repositioning, which is

unfavorable for maintaining tissue regeneration. To overcome these shortcomings, our team carried out innovative modifications to the TTT technique: optimizing the design of the bone transport external fixator, dividing the single transport bone fragment into two independent bone flaps, and adopting an innovative distraction mode. When the two bone flaps are repositioned toward the center, one bone flap stops moving near the repositioning site, maintaining sustained traction with the overlying skin and soft tissues. This strategy facilitates persistent tension stimulation of the periosteum and continuous promotion of capillary regeneration, providing a sustained biological driving force for wound healing [13].

Compared with conventional TTT, dual-bone flap traction modified TTT offers the following advantages. Firstly, dividing the single bone fragment into two smaller flaps for transport significantly reduces the stress area and pressure on local skin and soft tissues, effectively lowering the risk of compressive necrosis. Secondly, under the dual-bone flap traction mode, one bone flap is not completely repositioned after the transport cycle, providing sustained stimulation to the periosteum and surrounding soft tissues. This promotes more durable capillary neovascularization, creates a sustained bioactive microenvironment for wound healing, and consequently shortens the wound healing cycle. In this study, Group A exhibited obvious short-term therapeutic effects. At 1 month postoperatively, the improvements in ABI, skin temperature of the affected limb, and VAS pain score were significantly superior to those in Groups B and C.

At 1 week postoperatively, the improvement in skin temperature in Group A was inferior to that in Group C. This may be attributed to the transient increase in local skin temperature caused by acute inflammatory reactions following extensive debridement in Group C. In contrast, Group A was in the early stage of surgical trauma and initial tissue regeneration stimulation, during which the circulation-improving effect had not been fully manifested. The significant decline in skin temperature in Group C at 1 month postoperatively, after the resolution of acute inflammation, supports this inference. The marked effective rate at 3 months post-treatment in Group A was significantly higher than those in Groups B and C, and the healing time of small wounds was significantly shorter. However, no statistically significant difference was found in the recurrence rate within 6 months after small wound healing among the three groups. This result may be due to the limited sample size, and further studies with larger sample sizes are warranted for verification.

This study has several limitations. Firstly, the small sample size may affect the stability and statistical power of the results, with potential risks of bias. Secondly, due to limitations in follow-up methods, some patients were followed up via telephone and WeChat, without in-hospital revisit.

In conclusion, this study preliminarily demonstrates that dual-bone flap traction modified TTT is an effective and feasible approach for the treatment of DFU. Its innovative dual-bone flap design and sustained periosteal stretching strategy effectively reduce the complication risk of the

conventional procedure. By maintaining tension stimulation, it more effectively promotes microcirculatory regeneration and wound healing, particularly demonstrating outstanding long-term efficacy. Future multicenter, large-sample, long-term follow-up studies will contribute to a more comprehensive evaluation of its clinical value.

Conflict of interest None

Author Contributions Li Yingqing: study design, implementation, and manuscript drafting. Ye Dongcheng: manuscript revision and literature collection. Zeng Xinming, Wang Pengcheng: administrative, material, and surgical technical support. Yin Zhicheng, Hong Yongchang, Yuan Zhuohui: surgical participation, data collection, analysis and interpretation. Zhao Rongshan, Liang Weijian: patient management.

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· 论 著 ·

双骨瓣牵引式改良胫骨横向骨搬运术治疗 糖尿病足溃疡

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摘要: **目的** 探讨双骨瓣牵引式改良胫骨横向骨搬运术(TTT)在糖尿病足溃疡(DFU)治疗中的疗效,及其对患者患肢踝肱指数(ABI)、体表温度、视觉模拟评分(VAS)的影响。**方法** 回顾性选择2022年1月至2024年10月东莞市人民医院手外科收治的38例DFU患者,根据手术方式分为三组:A组($n=10$,行双骨瓣牵引式改良TTT)、B组($n=8$,行传统TTT)和C组($n=20$,行常规清创扩创术)。比较三组患者术前、术后1周、术后1个月患肢ABI、体表温度、VAS,以及治疗3个月后显效率、小创面痊愈时间、小创面痊愈后半年内复发率。**结果** 术后A组患肢ABI、体表温度、VAS短期改善明显,术后1个月时明显优于B组、C组($P<0.05$)。随访时间6~15个月,随访中,A组、B组和C组治疗3个月后显效率差异有统计学意义[100.0%(10/10)、75.0%(6/8)、40.0%(8/20), $\chi^2=10.925$, $P=0.004$]。A组、B组和C组小创面痊愈时间差异有统计学意义[(2.9±0.7)个月、(4.1±1.0)个月、(4.3±0.8)个月, $F=10.035$, $P=0.004$]。**结论** 双骨瓣牵引式改良TTT可显著改善患肢微循环、缩短创面愈合时间,其疗效显著优于传统TTT及常规清创扩创术。

关键词: 双骨瓣牵引;胫骨横向骨搬运术;糖尿病足;牵拉成骨;再生

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Clinical study on double bone flap traction-modified tibial transverse transport in the treatment of diabetic foot ulcers

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Abstract: Objective To investigate the efficacy of the double bone flap traction-modified tibial transverse transport (TTT) in the treatment of diabetic foot ulcers (DFU), and its impact on the ankle-brachial index (ABI), skin temperature, and Visual Analogue Scale (VAS) score of the affected limb. **Methods** A retrospective selection was made of 38 DFU patients admitted to the Department of Hand Microvascular Surgery of Dongguan People's Hospital from January 2022 to October 2024. According to the surgical method, they were divided into three groups: Group A ($n=10$, undergoing double bone flap traction modified TTT), Group B ($n=8$, undergoing traditional TTT), and Group C ($n=20$, undergoing conventional debridement and wound revision). The ABI, skin temperature, and VAS score of the affected limb were compared among the three groups before surgery, one week after surgery, and one month after surgery. The marked improvement rate after 3 months of treatment, the healing time of small wounds, and the recurrence rate within six months after healing of small wounds were also compared. **Results** After surgery, Group A showed significant short-term improvement in ABI, skin temperature, and VAS score of the affected limb, and these

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parameters were significantly better than those in Groups B and C at one month postoperatively ($P<0.05$). The follow-up period ranged from 6 to 15 months. During follow-up, there was a statistically significant difference in the marked improvement rate after 3 months of treatment among Groups A, B, and C [100.0% (10/10), 75.0% (6/8), 40.0% (8/20), $\chi^2=10.925$, $P=0.004$]. There was also a statistically significant difference in the healing time of small wounds among Groups A, B, and C [(2.9±0.7) months, (4.1±1.0) months, (4.3±0.8) months, $F=10.035$, $P=0.004$].

Conclusion The double bone flap traction-modified TTT can significantly improve the microcirculation of the affected limb and shorten wound healing time, and its efficacy is significantly superior to that of traditional TTT and conventional debridement and wound enlargement.

Keywords: Double bone flap traction; Tibial transverse transport; Diabetic foot; Distraction osteogenesis; Regeneration

Fund program: Dongguan Social Development Technology Project General Project (20211800903452)

我国糖尿病患病率正逐年提高,2019年已达12.4%^[1-2],其中有15%的患者合并糖尿病足^[3],且85%的患者以糖尿病足溃疡(diabetic foot ulcers, DFU)为首表现。DFU具有迁延不愈、治疗难度大等特点,截肢率达30%以上^[3-4]。踝关节以下的血管和神经病变是引发DFU的主要原因。当前,DFU的临床治疗仍依赖于清创、扩创术、创面持续负压引流、血供介入等外科治疗手段,但清创、扩创及创面持续负压引流主要针对创面治疗,无法从根本上改善患肢循环,故疗效欠佳^[5]。血管介入治疗,在踝关节以往的应用中具有明显的技术局限性,特别是直径<2 mm的血管开通率低,再狭窄率低,严重限制了其临床应用^[6]。近年来,胫骨横向骨搬运手术(tibial transverse transport, TTT)治疗在我国DFU的治疗中取得满意的效果,其核心技术原理是张力-应力法则,即生物组织被牵拉时会产生一定的张力,可刺激组织再生和持续生长,进而形成丰富的毛细血管网,加速创面愈合^[7-12]。主要适用于不伴有下肢大血管闭塞或闭塞后通过介入手段再通后的Wagner 2~4级的DFU。随着TTT技术的广泛应用,其局限性也逐渐显露,当骨块牵拉复位后,骨膜牵张^[13]刺激停止,毛细血管增生的促进作用也随之消失,导致创面愈合受限;此外,大块骨块搬运后,还会出现搬运皮缘坏死、牵拉骨块游离坏死^[14]。针对传统TTT的局限性,本研究团队通过改良骨瓣设计、优化外固定支架结构及调整骨搬运方式,使骨膜持续受到牵张刺激,维持毛细血管再生的促进因素,有效提高DFU的临床疗效。

1 资料与方法

1.1 一般资料 选取2022年1月至2024年10月东莞市人民医院手外科收治的影像学提示有下肢动脉病变的DFU患者38例。纳入标准:(1)长期(病史大于3个月)Wagner 3~4级的DFU患者;(2)下肢动脉

闭塞,但膝关节以下至少有1条动脉通至踝部,或经介入治疗后,再通至踝部;(3)手术意愿明确,且能耐受手术。排除标准:(1)依从性差,难以配合治疗;(2)严重凝血功能障碍;(3)膝以上血管闭塞,且无动脉分支血供到达小腿;(4)患有其他疾病严重并发症,不能耐受麻醉及手术。本研究项目已获得东莞市人民医院医学伦理委员会批准(伦理号KYKT2021-061),所有患者均对本项目知情并签署知情同意书。

患者按手术方式分为三组。A组($n=10$)采用双骨瓣牵引式改良TTT治疗。B组($n=8$)采用传统TTT治疗。C组($n=20$)行常规清创、扩创术。三组患者性别、年龄及Wagner分级差异无统计学意义($P>0.05$),具有可比性。见表1。

表1 三组一般资料比较

项目	A组($n=10$)	B组($n=8$)	C组($n=20$)	χ^2/F 值	P 值
性别[例(%)]					
男	8(80.0)	5(62.5)	16(80.0)	1.070	0.586
女	2(20.0)	3(37.5)	4(20.0)		
年龄(岁, $\bar{x}\pm s$)	71.1±7.3	66.0±11.2	63.9±9.5	1.972	0.154
Wagner分级[例(%)]					
3级	2(20.0)	2(25.0)	4(20.0)	0.095	0.954
4级	8(80.0)	6(75.0)	16(80.0)		

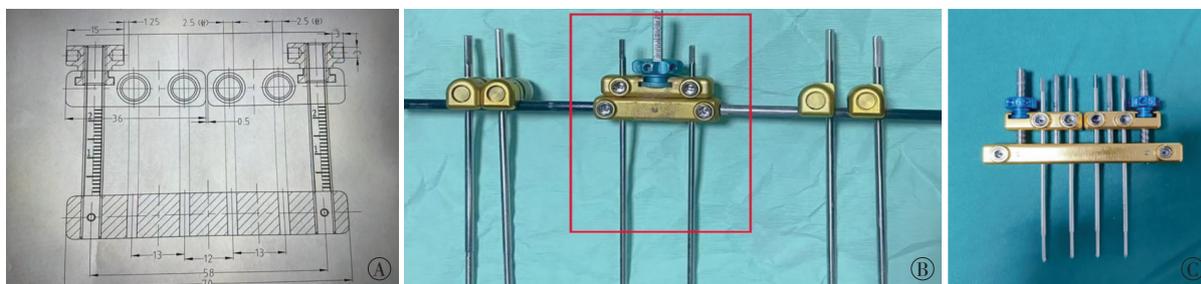
1.2 术前准备与手术器械 术前完善双下肢动脉彩超及CT血管成像(computed tomography angiography, CTA)检查,严格控制血糖,目标值为空腹血糖<8 mmol/L,餐后血糖<12 mmol/L,纠正低蛋白血症及电解质紊乱。术前所有患者均测量并记录患肢踝肱指数(ankle brachial index, ABI)、温度、创面面积、创面深度及视觉模拟评分(visual analogue scale, VAS)。骨搬运外固定架包括大博胫骨搬运支架(厦门大博医疗器械,产品编号109970200)以及改良后的胫骨搬运支架(图1),该改良以大博胫骨搬运支架为基础,在原有的搬运座上,进行改良,设计成可分别独立搬运的两组可旋转按钮,分别搬运两片细小骨块。

1.3 手术方法与术后处理

1.3.1 A组 在胫骨中下段内侧(约胫骨结节以远5 cm处)作一长约5 cm弧形切口,切开皮肤、皮下组织至筋膜表面,确定胫骨的截骨范围,截骨长度约5 cm,宽度约1.5 cm。暴露胫骨,保留骨膜,向两侧按计划好的截骨范围切开骨皮质,形成可活动骨瓣,再将骨瓣两等分,形成两片2.5 cm×1.5 cm的骨瓣。在两骨瓣上下各置入1枚牵引针,而后在胫骨近端及远端分别平行置入2根外固定支架钢针,安装支架外固定,最后在外固定支架上装可活动的横向牵引器(图2)。术后处理,术后第5天复查患肢胫骨正侧位片,视局部伤口情况开始缓慢横向搬移两片胫骨骨窗,每天向上搬移1 mm,分6次完成,11 d后停止,

再次复查胫骨正侧位X线片后反向搬移两片胫骨骨窗,每天向下搬移1 mm,分6次完成,8 d后,上端骨瓣停止搬移,下端骨瓣继续向下搬移,向下搬移共11 d后,将胫骨远端骨窗放回原位,复查X线片,骨瓣复位5 d后,拆除骨搬移装置。在使用助行器的情况下允许患者进行部分负重。骨搬移期间,按项目设计计划定期观察并记录各指标值。

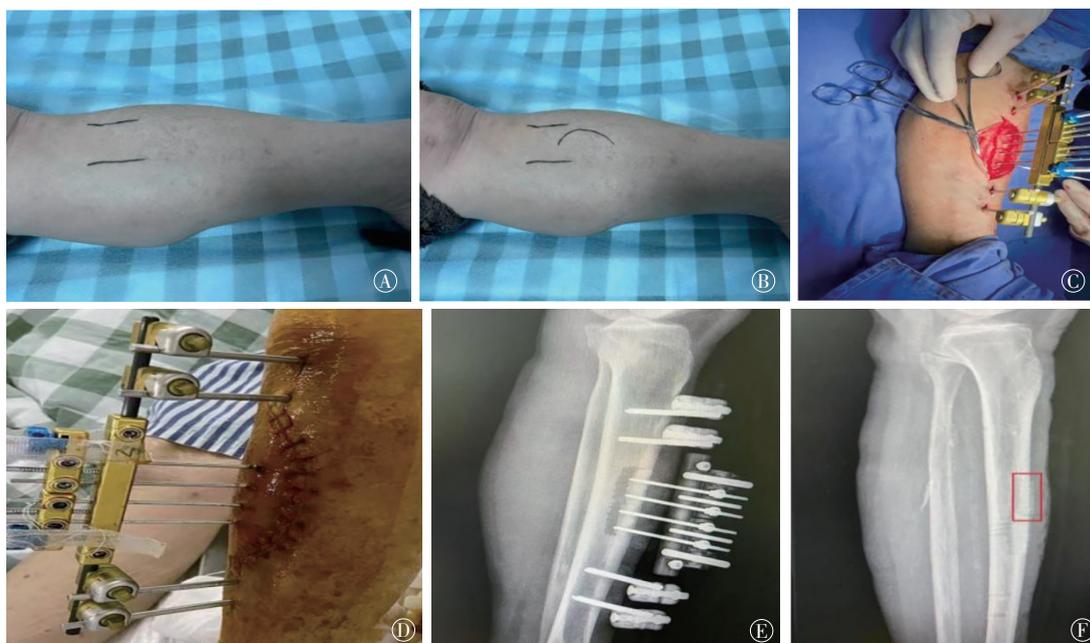
1.3.2 B组 采用A组的显露及截骨方式,但B组并未将骨瓣一分为二,采用传统的单一大块骨瓣搬移,并按A组方法安装传统骨搬移架。B组术后处理:术后常规处理同A组,术后第5天复查患肢胫骨正侧位片,视局部伤口情况开始缓慢横向搬移胫骨骨窗,每天向上搬移1 mm,分6次完成,11 d后停止,再次复查



注:A为骨搬移架改良设计图,在保证骨窗总面积不变的情况下,通过增加旋扭及骨针数量,实现同时可搬移两块细小骨瓣;B为传统骨搬移架,方框内所示为传统搬移架上的骨搬移座;C为改良后的骨搬移座。

图1 骨搬移座的改良设计图及成品图

Fig.1 Improved design and finished product of bone mover seat



注:A为术前体表定位及标记;B为切口设计;C为按手术步骤完成骨搬移架的安装;D为骨搬移第11天,骨瓣与胫骨分离后,术区外观(两块骨瓣与胫骨分离11 mm);E为骨搬移第11天,骨瓣与胫骨分离X线片(两块骨瓣与胫骨分离11 mm);F为搬移完毕,拆除外固定支架后,骨瓣与胫骨分离X线片(胫骨近端骨瓣比远端骨瓣高出3 mm)。

图2 改良TTT过程、术后创面情况及术后影像学情况

Fig.2 Improved TTT process, postoperative wound condition, and postoperative imaging findings

胫骨正侧位X线片后反向搬移胫骨骨窗,每天向下搬移1 mm,分6次完成,11 d后停止,将胫骨骨窗放回原位。1个月后复查X线片,根据骨愈合情况,拆除骨搬移装置,并在使用助行器的情况下部分负重,但需注意防跌倒。骨搬移期间,按项目设计计划定期观察并记录各指标值。

1.3.3 C组 术中不使用下肢止血带,以便术中判断组织活性,尽量保留活性组织,彻底清除坏死、感染的组织及炎性肉芽组织,充分打开窦道,以利引流,清创时清创深度以清创后创面有新鲜渗血为准。术后处理:术后隔日行手术创面清创换药,按项目设计计划定期观察并记录各指标值。

1.4 评价指标 (1) ABI,分别测量患者患侧踝部与上臂的收缩压,计算ABI^[15-17]。(2) 患肢温度,利用红外线测温仪,对病变侧肢体踝关节以远区域测温,测温方法为至少监测包含趾端在内的3个部位的体表温度,取其平均值^[15-17]。(3) VAS评分,根据患者疼痛感受记录患者患肢VAS分值^[15-17]。(4) 治疗3个月后显效率,疗效评定标准主要参照Texas分级^[18],病变下降2级,且溃疡面积缩小2/3以上视为治疗显效^[6]。(5) 小创面痊愈时间,痊愈评定标准为溃疡面完全愈合,无明显疤痕挛缩及功能障碍,局部血液循环良好,皮肤有光泽。因创面大小及深度的不同均能影响创面愈合时间,本研究统计Wagner分级为4级,且溃疡面积<5 cm²的创面痊愈所需时间。(6) 小创面痊愈后半年内复发率,在随访期内,统计各组创面痊愈后半年内的复发率。

1.5 统计学方法 采用SPSS 26.0软件进行统计分析。正态分布的计量资料以 $\bar{x}\pm s$ 表示,三组比较采用方差分析,两两比较采用SNK-*q*;多时点比较采用重复测量资料的方差分析。计数资料采用例(%)表示,组间比较采用 χ^2 检验。检验水准为0.05,双侧检验。

2 结果

2.1 三组ABI比较 三组手术前后交互效应显著($P<0.01$)。术前1 d三组ABI值差异无统计学意义($F=1.121, P=0.337$)。A组在术后1周及术后1个月均有改善,与术前1 d比较,差异有统计学意义($P<0.05$),而B组及C组均先升后降,差异有统计学意义($P<0.01$)。见表2。

2.2 患肢体表温度变化 三组手术前后交互效应显著($P<0.01$)。术前1 d三组温度差异无统计学意义($F=0.580, P=0.565$)。术后1周,三组患肢体表温度均显著高于术前,且B组显著低于A组和C组($P<0.05$)。A组患肢体表温度高于术前,与术后1个月比

较差异无统计学意义($P>0.05$)。术后1个月C组较术后1周有所降低($P<0.05$),且显著低于A组($P<0.05$)。见表3。

2.3 VAS评分比较 三组手术前后交互效应显著($P<0.01$)。术前1 d三组VAS评分差异无统计学意义($F=0.108, P=0.898$)。A组在术后1周及术后1个月均显著降低($P<0.05$),而B组及C组均先降后升,效果未能持续,差异有统计学意义($P<0.05$)。在术后1个月,A组显著低于B组、C组,差异有统计学意义($P<0.05$)。见表4。

2.4 创面愈合情况比较 三组治疗3个月后显效率差异有统计学意义($P<0.01$),A组显著高于C组($P<0.05$),但B组与A组和C组的差异无统计学意义

表2 三组手术前后ABI的比较 ($\bar{x}\pm s$)

Tab.2 Comparison of ABI among three groups before and after surgery ($\bar{x}\pm s$)

组别	术前1 d	术后1周	术后1个月
A组(n=10)	0.48±0.09	0.68±0.08 ^a	0.70±0.10 ^a
B组(n=8)	0.46±0.13	0.61±0.16 ^a	0.57±0.19
C组(n=20)	0.52±0.10	0.74±0.13 ^{ab}	0.54±0.13 ^{cd}
$F_{\text{组间}}/P_{\text{组间}}\text{值}$		7.893/0.001	
$F_{\text{时间}}/P_{\text{时间}}\text{值}$		144.672/<0.001	
$F_{\text{交互}}/P_{\text{交互}}\text{值}$		2.981/0.019	

注:与同组术前1 d时比较,^a $P<0.05$;与B组比较,^b $P<0.05$;与同组术后1周时比较,^c $P<0.05$;与A组比较,^d $P<0.05$ 。

表3 三组手术前后患肢温度的比较 ($^{\circ}\text{C}$, $\bar{x}\pm s$)

Tab.3 Comparison of the affected limb temperature among three groups before and after surgery ($^{\circ}\text{C}$, $\bar{x}\pm s$)

组别	术前1 d	术后1周	术后1个月
A组(n=10)	27.00±3.09	33.50±2.47 ^a	32.90±2.43 ^a
B组(n=8)	27.90±3.00	31.60±3.95 ^a	29.00±3.50
C组(n=20)	28.10±2.29	35.20±3.12 ^{ab}	30.00±4.17 ^{cd}
$F_{\text{组间}}/P_{\text{组间}}\text{值}$		4.256/0.019	
$F_{\text{时间}}/P_{\text{时间}}\text{值}$		87.534/<0.001	
$F_{\text{交互}}/P_{\text{交互}}\text{值}$		3.894/0.003	

注:与同组术前1 d比较,^a $P<0.05$;与B组比较,^b $P<0.05$;与同组术后1周比较,^c $P<0.05$;与A组比较,^d $P<0.05$ 。

表4 三组手术前后VAS评分的比较 (分, $\bar{x}\pm s$)

Tab.4 Comparison of VAS score among three groups before and after surgery (point, $\bar{x}\pm s$)

组别	术前1 d	术后1周	术后1个月
A组(n=10)	6.80±1.48	2.10±0.74 ^a	1.80±0.92 ^a
B组(n=8)	7.10±1.36	3.50±0.76 ^{ab}	4.10±1.73 ^a
C组(n=20)	6.90±1.33	3.80±1.44 ^{ab}	4.80±1.76 ^a
$F_{\text{组间}}/P_{\text{组间}}\text{值}$		5.782/0.005	
$F_{\text{时间}}/P_{\text{时间}}\text{值}$		213.459/<0.001	
$F_{\text{交互}}/P_{\text{交互}}\text{值}$		4.127/0.002	

注:与同组术前1 d时比较,^a $P<0.05$;与A组比较,^b $P<0.05$ 。

($P>0.05$)。A组小创面痊愈时间显著短于B组和C组($P<0.05$),但B组与C组的差异无统计学意义($P>0.05$)。三组小创面愈合后半年复发率差异无统计学意义($P>0.05$)。见表5。

2.5 典型病例 患者男性,72岁,因左足溃烂1个月入院。入院诊断为2型糖尿病,左足糖尿病足。Wagner分级为4级,入院后予左侧胫骨改良TTT治疗,术后恢复良好(图3)。此患者术前ABI为0.51,术后1周ABI为0.72,术后1个月ABI为0.79;术前患肢温度 $29.5\text{ }^{\circ}\text{C}$,术后1周患肢温度 $37.3\text{ }^{\circ}\text{C}$,术后1个月患肢温

度 $36.1\text{ }^{\circ}\text{C}$;术前VAS评分为5分,术后1周VAS评分为1分,术后1个月VAS评分为1分。

表5 三组创面愈合情况的比较

Tab.5 Comparison of wound healing among three groups

组别	治疗3个月后 显效率(%)	小创面痊愈时 间(月, $\bar{x}\pm s$)	小创面痊愈后 复发率(%)
A组(n=10)	100.0	2.9 ± 0.7	10.0
B组(n=8)	75.0	$4.1\pm 1.0^*$	25.0
C组(n=20)	40.0*	$4.3\pm 0.8^*$	40.0
χ^2/F 值	10.925	10.035	2.994
P值	0.004	0.004	0.224

注:与A组比较,* $P<0.05$ 。



注:A为术前左足溃疡创面情况,部分趾体组织干性坏死,溃疡深达骨质;B为行改良TTT治疗后1周,可见足底部创面明显肉眼组织增生;C为术后第2个月随访情况,跨趾创面基本闭合,足底部创面遗留绿豆大小肉眼芽创面,无炎症表现;D为术后第3个月随访情况,跨趾及足底创面已疤痕愈合,无渗血、渗液,趾端颜色红润,血运良好;E为术前下肢CTA检查,图像可见左足部血管网不明显;F为术后2个月复查下肢CTA情况,图像可见左足部血管网明显较前丰富。

图3 1例DFU患者接受改良TTT治疗后创面愈合的过程

Fig.3 The process of wound healing in a DFU patient undergoing modified TTT

3 讨论

本研究通过临床病例分析,初步证实了改良TTT在DFU治疗中的可行性与有效性。该术式在缓解下肢疼痛、改善末梢循环及促进创面愈合方面展现出显著优势,具有良好的临床应用前景。

DFU的核心病理机制在于外周血管病变及微循环障碍,常规治疗效果常不理想,改善下肢微循环是促进DFU愈合的基础。目前,血管介入治疗是改善

下肢循环的主流手段,能有效开通大中动脉,短期内提升患足血供。然而,其局限性在于无法处理细小及微动脉,且术后血管再狭窄或闭塞发生率较高,对微循环的整体改善效果有限。TTT技术是治疗DFU的一种成熟方法,能有效改善下肢微循环。该技术于1989年经Ilizarov教授通过动物实验确立,并于2000年由曲龙教授首次成功应用于临床治疗下肢缺血性疾病,2019年花奇凯团队进一步优化其在DFU中的治疗方案,取得满意疗效^[9]。

随着TTT技术的临床普及,其传统术式的并发症逐渐显现:手术切口大,通常10~15 cm;牵拉单一骨块可导致局部软组织应力集中,容易导致血供障碍、组织坏死;搬移周期长,延迟下地行走;骨块复位时间长,医源性骨折风险增高;复位后失去持续牵张刺激,不利于组织再生维持。针对这些不足,本研究对TTT技术进行了创新性改良:改良骨搬移支架设计,将单一搬移骨块分割为两个独立骨瓣,通过创新性的搬移方式,实现两个骨瓣向中心复位时,其中一个骨瓣在接近复位位置时停止移动,使其与覆盖的皮肤软组织保持持续牵引状态。有利于维持对骨膜的张力刺激,持续促进毛细血管再生,为创面愈合提供持久的生物学动力^[13]。

相较于传统TTT,双骨瓣牵引式改良TTT具有以下优势:首先,将单一骨块分割为两个较小骨瓣进行搬移,显著减小了局部皮肤软组织的受力面积与压强,有效降低了局部皮肤软组织压迫性坏死风险;其次,在“双骨瓣牵引”模式下,搬移周期结束后,其中一骨瓣未完全复位,可持续刺激骨膜及周围软组织,能更持久地促进毛细血管新生,为创面愈合提供持续的生物活性环境,从而缩短创面愈合周期。

本研究中,A组短期治疗效应明显,其在术后1个月时,ABI、患肢皮温、VAS疼痛评分的改善程度均显著优于B组和C组。而在术后1周,A组在皮温改善上不及C组,考虑为C组患者接受大范围清创后,手术创伤引发的急性炎症反应可导致局部皮温一过性升高;而A组此时正处于手术创伤与组织再生刺激的早期阶段,其促进循环的效应尚未充分显现。术后1个月时,急性炎症反应消退,C组皮温显著回落,支持了这一推断。A组治疗3个月后显效率显著高于B组和C组,小创面痊愈时间显著短于B组和C组。而小创面愈合半年后复发率差异无统计学意义,推测此结果的原因可能在于样本量有限,有待更大样本数量的进一步研究进行验证。

本研究存在以下局限性:首先,样本量有限,可能影响结果的稳定性和统计效力,存在潜在偏倚风险;另外,由于随访方式的局限性,部分患者通过电话及微信随访,未能回院面访。

综上所述,本研究初步证明双骨瓣牵引式改良TTT是治疗DFU的一种有效的可行方法。其创新性

的双骨瓣设计及骨膜持续牵策略,有效降低了传统术式的并发症风险,并通过维持张力刺激更有效地促进了微循环再生和创面愈合,尤其在长期疗效上表现突出。未来的多中心、大样本、长期随访研究将有助于更全面地评估其价值。

利益冲突 所有作者均声明无利益冲突

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