Delayed Reconstruction of the Perforator Pedicle Propeller Flap after the Induced Membrane Technique for Gustilo IIIB Open Distal Tibial Fracture

Verzögerte Rekonstruktion des Perforator-Pedikel-Propellerlappens nach der induzierten Membrantechnik bei offener distaler Tibiafraktur von Gustilo IIIB

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ABSTRACT

Objective

This study aimed to evaluate the safety and efficacy of delayed reconstruction of the perforator pedicle propeller flap after the induced membrane technique in the treatment of Gustilo IIIB open distal tibial fracture, and to evaluate the clinical outcome and complications of two different perforator pedicle propeller flaps.

Methods

Thirty-four patients with Gustilo IIIB open distal tibial fractures treated by the induced membrane technique and delayed reconstruction of two different perforator pedicle propeller flaps from May 2017 to March 2022 were retrospectively analyzed. Patients were divided into two groups according to the different kinds of perforator pedicle propeller flaps covered. The operation required two stages. The Radiographic Union Score for Tibial fractures (RUST) was used to evaluate the healing of the tibial bone defect. The American Orthopaedic Foot and Ankle Society (AOFAS) score was used to evaluate ankle function. The complications associated with the technique were recorded.

Results

The number of serial debridements, excluding those performed during emergency and final operations, was a mean of 2.28 ± 0.83 in the PAPF group and 2.19 ± 0.83 in the PTAPF group. The PAPF group had a mean bone defect length of 6.76 ± 0.69 cm, the median healing time of

13.11 ± 0.96 months, RUST score 12.68 ± 1.63, and AOFAS score of 84.12 ± 6.38. On the other hand the PTAPF group's mean bone defect length was 6.73 ± 0.95 cm, the median healing time 12.63 ± 1.46 months, RUST score 13.73 ± 1.53 and AOFAS score 82.79 ± 5.49. There were no observed significant differences between the two groups in the number of serial debridements, bone defect length, bone union time, RUST score, or AOFAS score (p > 0.05). Flap size ranged from 9×6 cm^2 to 14×7 cm^2 in the PAPF group and from 9×6 cm^2 to 13×7 cm^2 in the PTAPF group. There were no severe complications such as flap-related complications or amputation. The differences in complications in the two groups were not statistically significant.

Conclusion

In cases of severe open tibial fracture, the reconstructive method is important. When delayed reconstruction is inevitable, surgeons should first perform radical debridement, followed by vacuum sealing drainage as a bridging therapy; both PAPF and PTAPF can be considered for definitive soft tissue coverage.

ZUSAMMENFASSUNG

Ziele

Ziel dieser Studie war es, die Sicherheit und Wirksamkeit der verzögerten Rekonstruktion des Perforator-Pedikel-Propellerlappens nach der induzierten Membrantechnik bei der Behandlung der offenen distalen Tibiafraktur von Gustilo IIIB zu untersuchen. Des Weiteren wurden die klinischen Ergebnisse sowie die Komplikationen von 2 verschiedenen Perforator-Pedikel-Propellerklappen bewertet.

Methoden

Bei der Studie handelt es sich um eine retrospektive Analyse von 34 Patienten mit offenen distalen Tibiafrakturen nach Gustilo IIIB. Die Patienten wurden von Mai 2017 bis März 2022 mit der induzierten Membrantechnik und der verzögerten Rekonstruktion von 2 verschiedenen Perforator-Pedikel-Propellerklappen behandelt. Die Patienten wurden in 2 Gruppen eingeteilt, je nachdem, welche Art von Per-

forator-Pedikel-Propellerklappen für die Behandlung verwendet wurde. Die Operation umfasste 2 Phasen. 1. Stufe: Der Radiographic Union Score für Tibiafrakturen (RUST) wurde verwendet, um die Heilung des Tibiaknochendefekts zu beurteilen. 2. Stufe: Der Score der American Orthopaedic Foot and Ankle Society (AOFAS) wurde verwendet, um die Knöchelfunktion zu bewerten. Die mit der Technik verbundenen Komplikationen wurden entsprechend erfasst.

Ergebnisse

Die Anzahl der seriellen Debridements, mit Ausnahme derjenigen, die während der Notfall- und Abschlussoperationen durchgeführt wurden, betrug in der PAPF-Gruppe durchschnittlich 2,28 ± 0,83 und in der PTAPF-Gruppe 2,19 ± 0,83. Die PAPF-Gruppe hatte eine durchschnittliche Knochendefektlänge von 6,76 ± 0,69 cm, eine mediane Heilungszeit von 13,11 ± 0,96 Monaten, einen RUST-Score von 12,68 ± 1,63 und einen AOFAS-Score von 84,12 ± 6,38. Bei der PTAPF-Gruppe hingegen betrug die durchschnittliche Knochendefektlänge 6,73 ± 0,95 cm, die mediane Heilungszeit 12,63 ± 1,46 Monate, der RUST-Score 13,73 ± 1,53 und der AOFAS-Score 82,79 ± 5,49. Es wurden keine signifikanten Unterschiede zwischen den beiden Gruppen in Bezug auf die Anzahl der seriellen Débridements, die Länge des Knochendefekts, die Knochenaufbauzeit, den RUST-Score oder den AOFAS-Score beobachtet (p > 0,05). Die Klappengröße reichte von 9×6 cm^2 bis 14×7 cm^2 in der PAPF-Gruppe und von 9×6 cm^2 bis 13×7 cm^2 in der PTAPF-Gruppe. Es traten keine schwerwiegenden Komplikationen wie Lappenkomplikationen oder Amputationen auf. Die Unterschiede bei den Komplikationen in den beiden Gruppen waren statistisch nicht signifikant.

Schlussfolgerung

Die rekonstruktive Methode spielt bei schweren offenen Tibiafrakturen eine sehr wichtige Rolle. In Fällen, in denen eine verzögerte Rekonstruktion unumgänglich ist, sollte der Chirurg zunächst ein radikales Débridement durchführen, gefolgt von einer Vakuum-Drainage als Überbrückungstherapie. Schließlich können PAPF und PTAPF für eine definitive Weichteilabdeckung in Betracht gezogen werden.

Introduction

Open distal tibial fracture is a relatively common injury, with a reported annual incidence of about 3.4 per 100,000 [1, 2]. This kind of fracture commonly results from high-energy trauma [3]. Because of the subcutaneous location of the tibia, segmental bone defects occur in about 70% of distal tibial fractures [4, 5]. The treatment of such fractures is very challenging owing to the risk of soft tissue necrosis, bone defects, surgical site infection, and osteomyelitis. The amputation rate among patients with Gustilo grade IIIB/C open fractures is as high as 27% [6].

The main purpose of open fracture treatment is to repair the bone defect and perform soft tissue reconstruction. However, the optimal timing of tissue transfer and method of bone repair remain controversial. The British Orthopaedic Association Standards for Trauma recommends that soft tissue closure or coverage should be achieved within 72 hours of injury [7]. However, the patient's general condition may preclude emergency surgery and it is often difficult to accurately evaluate fractures preoperatively, including the vascular status, degree of soft tissue damage, and deep vein thrombosis. The two most important factors in the sur-

gical treatment of segmental bone loss are the bone loss size and absence of infection. Bone defects of less than 5 cm may be treated with autologous bone grafting, while bone defects greater than 5 cm may be amenable to treatment with a vascularized fibular graft or internal transport with an external fixator [8, 9]. The French surgeon Masquelet designed a two-stage technique for the treatment of large bone defects. In the first stage, an induced membrane is created using a bone cement spacer; in the second stage, a bone graft is used to repair the bone defect [10]. This induced membrane technique has been proven effective for the treatment of osteomyelitis and bone tumors [11, 12, 13, 14, 15].

Previous studies reported on perforator flap and free flap combined with the Masquelet technique and internal fixation for Gustilo IIIB open lower limb fracture [16, 17]. However, the studies still have some details that need to be discussed. The purposes of the present study were to (1) introduce the surgical method of vacuum sealing drainage (VSD) combined with delayed perforator pedicle propeller flap and the induced membrane technique for Gustilo IIIB open distal tibial fracture; (2) evaluate the clinical outcome and complications of the two different perforator pedicle propeller flaps; and (3) describe the advantages of this surgical method.

Patients and Methods

Patients

The data of 34 consecutive patients (25 men, 9 women) with Gustilo IIIB open distal tibial fracture treated by the Masquelet method combined with microsurgical techniques from May 2017 to March 2022 were retrospectively analyzed. Patients who suffered from Gustilo IIIB open distal tibial fracture were included in the study if (1) skin defects were present on the ankle and foot with exposed bones and tendons that could not be treated with a free skin graft; and (2) both the recipient and donor sites were amenable to the principles of perforator flap application. Patients with injured posterior tibial artery vessels or peroneal artery vessels, traumatic donor site skin defects, uncontrolled diabetes mellitus, and patients who did not want to participate in the procedures were excluded from the study. The mechanisms of injury were traffic accidents (n = 21), industrial injuries (n = 7), and falls (n = 6). All 34 patients had an open fracture of the distal third of the tibia that was classified as Gustilo IIIB. The preoperative Mangled Extremity Severity Score (MESS) ranged from 5 to 9, and the mean time from injury to surgical debridement was 8.6 hours (range 6–13 hours). Patients were divided into two groups according to the different kinds of perforator pedicle propeller flap covered. In the peroneal artery perforator pedicle propeller flap (PAPF) group (n = 18), a PAPF was used to cover the soft defect. In the posterior tibial artery perforator pedicle propeller flap (PTAPF) group (n = 16), the wound was reconstructed using a PTAPF.

The following data were retrospectively reviewed: patient age, sex, mechanism of injury, fracture location, method of fracture fixation, number of serial debridement and VSD applications, interval from injury to flap coverage, sizes of soft tissue and bone defects, flap type and size, bone union time, ankle function, complications including infection (defined as superficial infection, the presence of culture-positive osteomyelitis, infected nonunion, cel-
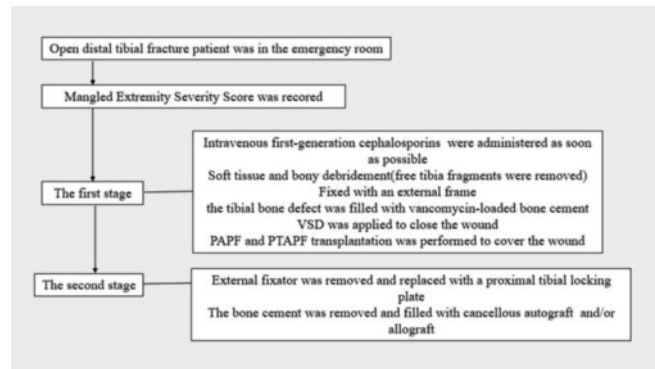
▶ **Fig. 1** Step-by-step treatment flowchart.

lulitis, or abscess requiring treatment), flap-related complications (defined as total flap loss, partial flap loss, or return to the operating room in the postoperative period for impending flap failure), amputation (performed for uncontrollable soft tissue or bone infection, non-reconstructable tissue or bone loss, or when the patient could not tolerate prolonged wound complication and management), and duration of follow-up.

The study received approval from the local ethics committee of our hospital (NO.SL-YX[YS]2023–015).

Surgical procedure

For all patients, the treatment was partitioned into two stages (▶ **Fig. 1**). The first stage comprised soft tissue and bony debridement, stabilization with external fixation, initiation of intravenous antibiotics, and wound closure with a flap. The second stage comprised the Masquelet technique. All operations were performed by one surgeon who specialized in reconstruction of traumatic limb injuries.

First stage Radical debridement of the necrotic and contaminated soft tissues was performed, and the contaminated soft tissue was obtained for bacterial culture. Small and large severely contaminated bone fragments were removed. A drill and osteotome were used to resect about 5 mm of bone on each side of the fracture site; high-energy technology was not used to minimize possible heat damage to the bone. After debridement, limited external fixation was performed and the limb length was restored. If the fractured ends of the tibia and fibula could be exposed at the wound site of the open fracture, the tibia and fibula were reduced and fixed. Otherwise, only the tibia was reduced and fixed. Depending on the lengths of the tibial defects, an appropriate dose of gentamicin sulfate with bone cement (mainly composed of polymethyl methacrylate [PMMA]) was applied. PMMA beads were used to fill the medullary cavity of the fracture site. The cement was wrapped at both ends of the fracture site to ensure that the entire length of the fractured bone was covered to form an induced membrane. VSD was applied to close the wound. Postoperatively, empirical anti-infection therapy was administered. If the bacterial culture indicated infection with specific bacteria, the appropriate antibiotics were administered. After VSD, the dressing was removed. If there was still necrotic tissue present, VSD was re-
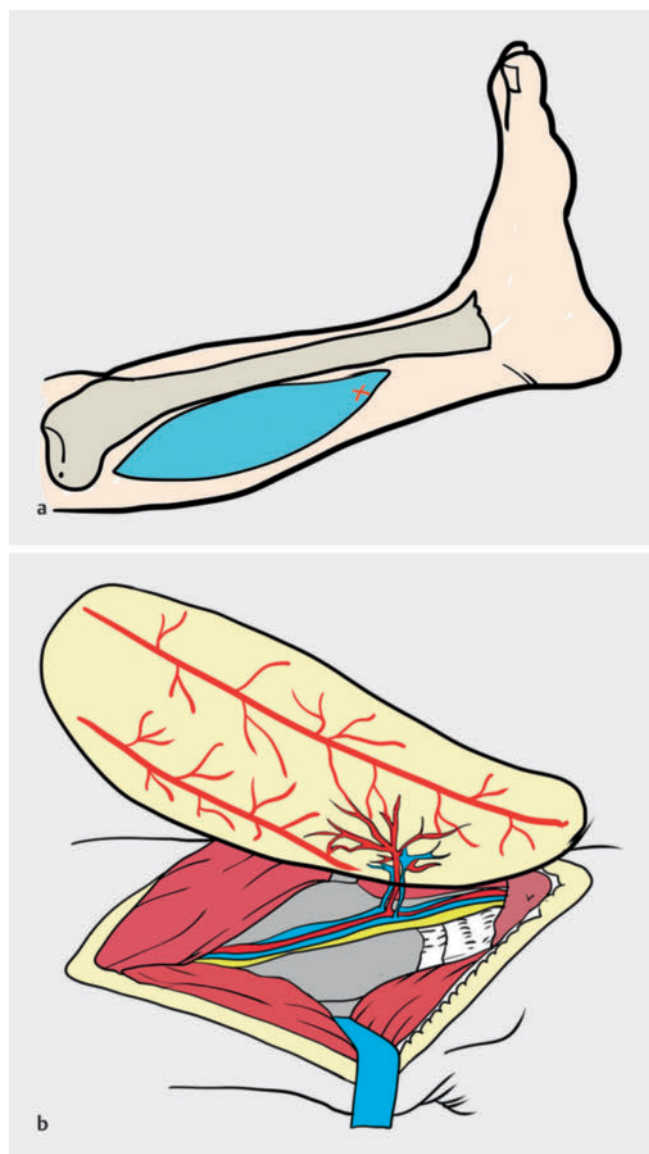
▶ **Fig. 2** Design of a posterior tibial artery freestyle perforator-based pedicle propeller flap. **a** The posterior tibial artery pedicled propeller flap is based on a perforator located proximal to the defect. This vessel serves as the pivot point of the flap. To mark the length of the flap, the distance from the perforator to the distal edge of the defect is noted. The width of the flap was equal to that of defect. The flap is completely elevated and is attached to the donor site only with the perforating vessels. The great saphenous vein and nerve are dissected free from the flap and left intact. **b** The accompanying vessels are divided meticulously from the posterior tibial artery and vein and are included in the flap. Loose perivascular tissue around the perforating vessels is carefully removed to reduce the likelihood of strangulation of the perforator during flap rotation.

peated until the wound surface was covered with new granulation tissue. Flap transplantation was performed when the bacterial culture from the tissue was negative. The posterior tibial artery perforator vessels (or peroneal artery perforator vessels) that were proximal to the defect were preoperatively marked using computed tomography angiography (CTA) and color Doppler sonogra-

phy (CDS). The size of the soft tissue defect was measured after debridement. To mark the length of the flap, the distance from the perforator to the distal edge of the defect was noted. The width of flap was equal to that of defect. The flap was initially incised along the lateral border. With the help of loupe magnification, the great saphenous vein, superficial peroneal nerve, and saphenous nerve coursing through the proposed flap were dissected out and preserved in all patients. The perforator was isolated cautiously from the posterior tibial artery and vein or peroneal artery and vein. The flap was harvested as an island above or below the deep fascia, and only the terminal perforator was used as the pedicle (▶ **Fig. 2**). Great caution must be applied when trimming the loose perivascular tissue in order to decrease the possibility of perforator strangulation after the flap is rotated. It is of utmost importance to wait and monitor the arterial perfusion for a few minutes before rotating the flap. If no vascular dysfunction was observed, then the flap was rotated to cover the recipient site. The remaining wound was treated with a free skin graft, if necessary, although direct closure was preferred when handling the donor site without tension on the flap edges when possible. Drains were then carefully positioned at the end of the procedure. The type of flap was selected in accordance with the tibial defect, amount of bone exposure, and location. A PAPF was used in 18 cases, while a PTAPF was used in 16 cases.

Second stage The second stage was performed about 9 weeks after the flap transplantation, by which time the flap and surrounding tissues were well healed. The bone defect was carefully dissected to protect the well-healed wounds from damage. A sharp incision was made through the induced biomembrane. An osteotome was then used to cut the cement spacer into small pieces so that it could be removed. The defect was fixed with a proximal tibial locking plate. A cancellous autograft was then harvested. Large bone defects were treated with an allograft that accounted for 1/3 of the graft. The entire defect space was surrounded by the graft so that the ends of the bone were covered by at least 5 mm. If possible, the soft tissue was repaired by returning the membrane to its original position and completely covering the graft.

Postoperative protocol

Patients were permitted to perform passive and active movements immediately postoperatively, and to perform non-weightbearing activities at 4 weeks after the second-stage surgery. Full weightbearing was allowed after radiological union was obtained.

Evaluation of clinical outcome

The Radiographic Union Score for Tibial fractures (RUST) [18] was used to evaluate the healing of the tibial bone defects implanted with autogenic cancellous and allograft bone. The American Orthopaedic Foot and Ankle Society (AOFAS) scale was used to evaluate the ankle function. All outcomes were assessed by the same follow-up group who were blinded to the surgical procedures performed. The mean interval from injury to flap coverage, interval from flap coverage to bone cement removal, length of the bone defect, and time to radiological union were calculated. Complications such as infection and flap failure were recorded.

Statistical analysis

All continuous data are presented as the mean ± SD. All data were statistically analyzed using SPSS 22.0 (IBM Cop., Armonk, NY, USA). Student's t-test was used to compare differences in the time from injury to flap coverage, the number of serial debridements and VSD applications, bone defect length, bone union time, RUST score, and AOFAS score between the two groups. Chi-square tests was used to compare differences in complications in the groups. Values of p < 0.05 were considered to be significantly different.

▶**Table 1** Patient demographics.

No.	Gender	Age at accident	No. of serial debridements and VSD application	Segment and bone defect length (cm)	Size of soft tissue defect (cm²)	Flap and flap size (cm²)	Bone union time (months)	Complications
1	M	71	3 and 4	5.6	9 × 6	PAPF 10 × 7	13	None
2	M	59	3 and 4	7.5	8 × 5	PTAPF 9 × 6	11	None
3	M	30	1 and 2	4.8	12 × 6	PTAPF 13 × 7	12	None
4	F	55	2 and 3	6.8	13 × 5	PAPF 14 × 6	12	None
5	M	51	2 and 3	6.3	11 × 5	PAPF 12 × 6	12	Superficial infection
6	M	48	3 and 4	6.0	10 × 7	PTAPF 11 × 8	13	None
7	F	46	3 and 4	6.8	13 × 5	PAPF 14 × 6	15	None
8	M	44	4 and 5	5.8	12 × 6	PAPF 13 × 7	15	None
9	F	68	3 and 4	7.4	13 × 5	PTAPF 14 × 6	14	None
10	M	62	3 and 4	6.7	13 × 6	PAPF 14 × 7	14	None
11	M	57	2 and 3	8.3	13 × 6	PAPF 14 × 7	13	None
12	M	70	2 and 3	5.8	9 × 6	PAPF 10 × 7	12	None
13	F	41	3 and 4	6.6	12 × 6	PTAPF 13 × 7	13	None
14	M	48	1 and 2	6.2	10 × 5	PTAPF 11 × 6	11	None
15	M	61	2 and 3	8.6	11 × 6	PTAPF 12 × 7	14	Epidermis necrotic
16	F	29	2 and 3	7.2	8 × 5	PAPF 9 × 6	12	None
17	M	28	3 and 4	6.8	9 × 6	PAPF 10 × 6	13	None
18	M	64	2 and 3	7.2	8 × 6	PAPF 9 × 6	12	None
19	M	54	3 and 4	7.4	10 × 5	PTAPF 11 × 6	11	None
20	M	39	2 and 3	6.5	11 × 5	PTAPF 12 × 6	15	None
21	F	70	3 and 4	7.3	10 × 6	PTAPF 11 × 7	11	None
22	M	57	1 and 2	7.2	13 × 6	PAPF 14 × 6	14	None
23	M	50	2 and 3	6.7	12 × 5	PAPF 13 × 6	13	None
24	M	28	3 and 4	6.0	13 × 5	PTAPF 14 × 6	12	None
25	F	55	2 and 3	7.0	12 × 5	PTAPF 13 × 6	13	None
26	M	52	1 and 2	6.8	11 × 6	PAPF 12 × 6	13	None
27	M	29	2 and 3	5.6	12 × 6	PTAPF 13 × 7	14	None
28	F	45	3 and 4	7.2	13 × 6	PAPF 14 × 7	14	None
29	M	50	1 and 2	7.0	13 × 5	PTAPF 14 × 6	15	Epidermis necrotic
30	M	72	3 and 4	7.2	12 × 5	PAPF 13 × 6	13	None
31	M	56	2 and 3	7.4	11 × 6	PAPF 12 × 7	13	None
32	M	57	1 and 2	7.8	12 × 5	PTAPF 13 × 6	12	None
33	M	72	2 and 3	6.0	13 × 5	PTAPF 14 × 6	11	None
34	F	70	1 and 2	5.8	12 × 5	PAPF 13 × 6	13	None

▶Table 2 Number of serial debridements and VSD, bone defect length, bone union time, RUST score, and AOFAS score in two groups (mean ± SD).

	No. of serial debridement applications	No. of VSD applications	bone defect length (cm)	Bone union time (months)	RUST score	AOFAS score
PAPF	2.28 ± 0.83	3.28 ± 0.83	6.76 ± 0.69	13.11 ± 0.96	12.68 ± 1.63	84.12 ± 6.38
PTAF	2.19 ± 0.83	3.19 ± 0.83	6.73 ± 0.95	12.63 ± 1.46	13.73 ± 1.53	82.79 ± 5.49
t	0.317	0.317	0.086	1.134	1.94	0.65
P	0.754	0.754	0.932	0.267	0.06	0.52

VSD: vacuum sealing drainage, RUST: Radiographic Union Score for Tibial fractures, AOFAS: American Orthopaedic Foot and Ankle Society

Results

A total of 34 patients with Gustilo IIIB open distal tibial fracture treated by the Masquelet method combined with microsurgical techniques from May 2017 to March 2022 were included (▶ Table 1). The patients were followed up for 11 to 28 months (mean 19 ± 3.78 months). The mean time from injury to flap coverage and the interval between the flap transplantation and the second stage was, respectively, 9.21 ± 3.69 days and 9.31 ± 1.23 weeks in the PAPF group and 8.92 ± 4.79 days and 8.96 ± 1.24 weeks in the PTAPF group. There was no statistically significant difference (p > 0.05). The number of serial debridement applications (excluding those performed during emergency and final operations), the mean bone defect length, the median healing time, RUST score, and AOFAS score was, respectively, 2.28 ± 0.83, 6.76 ± 0.69 cm, 13.11 ± 0.96 months, 12.68 ± 1.63, and 84.12 ± 6.38 in the PAPF group and 2.19 ± 0.83, 6.73 ± 0.95 cm, 12.63 ± 1.46 months, 13.73 ± 1.53, and 82.79 ± 5.49 in the PTAPF group. No significant differences were observed between the two groups in the number of serial debridement applications, bone defect length, bone union time, RUST score, and AOFAS score (p > 0.05; ▶ Table 2). Flap size ranged from 9 × 6 cm^2 to 14 × 7 cm^2 in the PAPF group and from 9 × 6 cm^2 to 13 × 7 cm^2 in the PTAPF group. There were no severe complications, including flap-related complications and amputation. The flaps survived in all patients. Part of the epidermis at the distal edge of the flap was necrotic but healed after dressing changes in two patients in the PTAPF group. One patient suffered from wound superficial infection in the PAPF group. This difference was not statistically significant (p > 0.05). The donor sites healed without excessive scarring or pain.

Case examples

Case 1 A 48-year-old male suffered a machine-related crush injury, resulting in a Gustilo IIIB left distal tibia and fibula fracture. During the first stage, debridement was performed, and the wound was irrigated with 9 L of solution. All free bone fragments were removed, the tibia and fibula length was maintained, an external fixator was attached (bridging the ankle joint), and the fibula fracture was stabilized with Kirschner wire. The flap size was 14 × 6 cm, and the bone defect was 6.8 cm in length. The tibial

bone defect was filled with antibiotic-loaded bone cement. VSD was applied to close the wound. PAPF was used for definitive soft tissue coverage after debridement three times. Skin grafting was performed for any new granulation tissue that the flap did not cover. The second stage was initiated 9 weeks after the PAPF transplantation. An osteotome was used to cut the cement spacer into small pieces so that it could be removed. The defect was fixed with a proximal tibial locking plate. The entire defect space was surrounded by a cancellous autograft. Twelve months after implantation of the autogenous cancellous bone, the graft appeared completely integrated. The patient was satisfied with the outcome (▶ Fig. 3).

Case 2 A 39-year-old male suffered a machine-related crush injury, resulting in a Gustilo IIIB right distal tibia and fibula fracture. During the first stage, debridement was performed, and the wound was irrigated with 9 L of solution. All free bone fragments were removed, the tibia and fibula length was maintained, and an external fixator was attached (bridging the ankle joint). The flap size was 12 × 6 cm, and the bone defect was 6.5 cm in length. The tibial bone defect was filled with antibiotic-loaded bone cement. VSD was applied to close the wound. PTAPF was used for definitive soft tissue coverage after debridement two times. Skin grafting was performed for the donor site. The second stage was initiated 9 weeks after the PTAPF transplantation. An osteotome was used to cut the cement spacer into small pieces so that it could be removed. The defect was fixed with a proximal tibial locking plate. The entire defect space was surrounded by a cancellous autograft. Eleven months after implantation of the autogenous cancellous bone, the graft appeared completely integrated. The patient was satisfied with the normal plantar and dorsiflexion flexion of the ankle (▶ Fig. 4).

Discussion

Gustilo grade IIIB and IIIC open tibial fractures require aggressive multidisciplinary management to treat the associated extensive soft tissue injury and segmental bone loss. The optimal timing of soft tissue reconstruction in such cases is controversial, and it is difficult to repair long bone defects. Based on our experience with damage control surgery, we proposed a two-stage treatment plan to reconstruct Gustilo grade IIIB open distal tibial fractures using

▶ **Fig. 3** Images of a 48-year-old man with a left Gustilo IIIB open distal tibial fracture. **a** Open left distal tibial and fibula fracture with an anteromedial soft tissue defect. **b, c** Lateral and anteroposterior radiographs showing tibial and fibular fractures. **d** After debridement, the tibial fracture is reduced and externally fixated, and the fibula fracture is reduced and fixed with Kirschner wire. **e** The bone defect is filled with vancomycin-loaded bone cement. **f** The wound surface is covered with the peroneal artery perforator flap. **g, h** Radiography showing the tibial bone defect filled with vancomycin-loaded bone cement. **i, j** Flap survival at 6 weeks after the flap transplantation. **k, l** External fixator was removed at 9 weeks after the flap transplantation. **m** Intraoperative incision in the second-stage surgery and removal of the antibiotic-loaded bone cement. **n–q** Radiography showing the tibial fracture healing at 12 months after implantation of autogenous cancellous bone. **r–t** The ankle has normal plantar flexion, with impaired dorsiflexion.

▶ **Fig. 4** Images of a 39-year-old man with a right Gustilo IIIB open distal tibial fracture. **a** Lateral radiographs showing tibial and fibular fractures. **b** Open right distal tibial and fibula fracture with medial soft tissue and bone defect. **c** After debridement, the tibial fracture is reduced and externally fixated, and the bone defect is filled with vancomycin-loaded bone cement. **d** The wound surface is covered with the posterior tibial artery perforator pedicle propeller flap and skin grafting is performed for the donor site. **e** Flap survival at 8 weeks after the flap transplantation. **f–i** Radiography showing tibial fracture healing at 11 months after implantation of autogenous cancellous bone. **j–l** The ankle has normal plantar and dorsiflexion.

VSD combined with delayed perforator pedicle propeller flap transplantation and the induced membrane technique.

It is ideal to obtain immediate soft tissue coverage for open tibial fractures to reduce the risk of infection and increase the likelihood of bone union [19, 20, 21]. Early closure of open tibial fractures (within 7 days) reportedly results in better outcomes than delayed closure (after 7 days) [22]. However, flap transplantation is often delayed owing to instability of the patient's general condition, comorbid injuries, large and complex wound beds needing serial debridement, or insufficient granulation tissue for definitive coverage. Studies have not strictly agreed with the proposed 72-hour window for wound coverage and commonly describe acceptable intervals of up to 15 days after injury before reconstruction [23]. To prevent infection, VSD is commonly used as a bridging therapy from emergency surgery to definitive wound coverage. Several studies showed that using vacuum-assisted closure (VAC) therapy decreases the flap size and the need for a free flap [22]. In our series, the wounds were successfully closed after treatment with primary VSD closure and delayed definitive wound coverage. The number of serial debridement applications, excluding those performed during emergency and final operations, was a mean of 2.28 ± 0.83 in the PAPF group and 2.19 ± 0.83 in the PTAPF group. The number of VSD application was a mean of 3.28 ± 0.83 in the PAPF group and 3.19 ± 0.83 in the PTAPF group. No significant differences were observed between the two groups in the number of serial debridements and VSD application. The interval between the emergency operation and definitive coverage was > 7 days in two groups. Although delay may be associated with poor outcomes, in our report, the complications were 5.56 and 12.5% in the two groups, respectively. This result is very satisfactory compared to previous studies [24, 25].

Definitive flap coverage depends on numerous factors, including wound size, available local tissue, anatomic location, patient characteristics, and experience of the treating physicians. Despite our advances in recent years regarding surgical technique and overall knowledge of microsurgical reconstruction, the ideal flap for complex soft tissue defects of the lower extremities still remains quite controversial and unidentified [26, 27]. Either microvascular-free flaps or non-microvascular local flaps have all been used to cover soft tissue defects of the lower extremities. The use of free flaps can provide well-vascularized tissue of any size distant from the zone of injury. Additionally, free flaps can be performed without considering the position of the pedicle artery perforator. However, the PAPF or PTAPF is a relatively less time-consuming procedure in comparison with the free flap, as it avoids the complexity, the multiple surgical sites, and the extra costs associated with free flaps [28].

VAC benefits the proliferation of granulation tissue and prepares the wound bed for flap coverage. Although this may not eliminate the need for soft tissue coverage procedures, it may reduce the need for extensive surgical techniques to obtain adequate coverage [29]. A study of 32 patients with Gustilo type IIIB open tibial fractures treated with VAC therapy found that 78% received rotational muscle flaps, 4 (13%) received free muscle flaps, and only 3 (9%) required split-thickness skin grafts for definitive wound coverage [8]. In the present series, wound coverage was obtained using the PAPF in 18 patients and the PTAPF in 16 pa-

tients. Flap size ranged from 9×6 cm^2 to 14×7 cm^2 in the PAPF group and from 9×6 cm^2 to 13×7 cm^2 in the PTAPF group. The flaps survived in all patients. Part of the epidermis at the distal edge of the flap was necrotic but healed after dressing changes in two patients in the PTAPF group. One patient suffered from wound superficial infection in the PAPF group. This difference was not statistically significant ($p > 0.05$).

Open fractures due to lower extremity trauma are often accompanied by comminuted and multisegmental fractures of the tibia, and the removal of free bone fragments during debridement results in tibial bone defects. This remains a challenging situation for orthopedic and trauma surgeons. The main complications of vascularized bone transfers are necrosis and infection at both the donor and recipient sites. The main complications of bone transports using the Ilizarov technique include a long treatment time, pain, pin tract infection, nonunion, and wearing discomfort [30, 31]. The Masquelet technique results in the formation of an induced membrane using an antibiotic-loaded bone cement spacer. The induced membrane promotes the healing of the bone graft, while the antibiotic-loaded bone cement spacer prevents wound infections by releasing antibiotics. A study of 15 patients treated using this technique reported a bone union rate of 100%, with a low infection rate [17]. Either intramedullary nails (IMN) or plates have all been used to fix a tibial defect after removing the cement spacer. Giannoudis et al. [32] performed a prospective study of the femur (14–10 by nail, 4 by plate), tibia (10–9 by plate and 1 by Ilizarov frame), and foot as well as upper extremity fractures (20) to evaluate the results of treatment with the induced membrane technique. Union was 93% after an average of 5.4 months. However, they did not compare the outcomes for plates versus nails fixation. Karger et al. [33] retrospectively reviewed 84 cases with tibia, femur, and forearm posttraumatic bone defects. Here, 89% of the injuries were due to open fractures with bone loss. However, they did not directly compare rates of union and number of reoperations based on fixation type. Taylor et al. [34] retrospectively reviewed 69 cases with the tibia (35), femur (16), and other bony defects (18) treated with the induced membrane technique. They found that fixation did not correlate with union. In our study, the bone cement was removed 9 weeks after flap transplantation and replaced with autogenic cancellous and allograft bone. The defect was fixed with a proximal tibial locking plate. The mean bone defect length, median healing time, mean RUST score, and mean AOFAS score was, respectively, 6.76 ± 0.69 cm, 13.11 ± 0.96 months, 12.68 ± 1.63, and 84.12 ± 6.38 in the PAPF group and 6.73 ± 0.95 cm, 12.63 ± 1.46 months, 13.73 ± 1.53, and 82.79 ± 5.49 in the PTAPF group. No significant differences were observed between the two groups in bone defect length, bone union time, RUST score, and AOFAS score. This indicated that both PAPF and PTAPF can be considered for definitive soft tissue coverage. The advantages of this method include the following [28, 35]:

1. Comparing our methodology with that of other publications, several previous studies have focused on the timing of definitive reconstruction; however, we found that the reconstructive method is more important in open fractures.

2. Delayed closure enables performance of radical and complete debridement procedures, which are more important than the timing of coverage.
3. The propeller flaps are a relatively less time-consuming procedure, as it avoids the complexity, the multiple surgical sites, and the extra costs associated with free flaps.

The present study has some limitations. First, the study was a retrospective study with a small sample size and relatively short follow-up period, which may limit the power of the results. Second, this is not a comparative study of early and delayed closure of Gustilo IIIB open tibial fractures. Third, in the second-stage surgery, we performed internal fixation using tibial locking plates rather than intramedullary nails, which may have affected the fracture healing time. However, we believe that our study also has several strengths. The study included patients with Gustilo IIIB open distal tibial fractures managed using a uniform treatment process comprising radical debridement, VSD, and final reconstruction with perforator pedicle propeller flaps. This enabled a reliable comparison of outcomes, including complication rate, flap survival rate, ankle function, and bone union. In addition, all surgeries were performed by one orthopedic surgeon and one plastic surgeon, which minimized technical errors. A prospective, randomized, controlled study is warranted to add to the results of this preliminary study.

Conclusion

For severe open tibial fractures, it is ideal to obtain early closure, within 7 days of injury. However, patients with such fractures often have multiple traumatic injuries, which delay reconstruction. We propose that open fracture treatment should focus on the method rather than the timing (early or delayed) of soft tissue coverage after radical debridement. The results of our uniform treatment process using VSD combined with delayed reconstruction of the posterior tibial artery perforator flap or peroneal artery perforator flap transplantation and the induced membrane technique for Gustilo IIIB open distal tibial fractures suggest that perforator pedicle propeller flap transfer may be considered for delayed reconstruction of severe open tibial fractures.

Conflict of Interest

The authors declare that they have no conflict of interest.

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