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Original Article

Management of Tibial Infected Nonunion with Segmental Bone Defect by the Ilizarov Technique

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Abstract

Background and Objective: Managing tibial fractures complicated by extensive bone loss, soft tissue defects, and infected nonunion remains a significant orthopedic challenge. While techniques like vascularized bone grafts or bone transport exist, they often fail to address infection and nonunion simultaneously. This study evaluates the effectiveness of the Ilizarov technique in simultaneously managing these complex tibial defects. **Patients and Methods:** A retrospective analysis was conducted on 79 patients (aged 12–60 years) with tibial diaphyseal defects > 5 cm treated using the Ilizarov technique between 2004 and 2016. The cohort comprised 67 open fractures (84.8%) and 12 closed fractures with postoperative infections (15.2%). Etiologies included gunshot injuries (n=53, 67.1%), traffic accidents (n=21, 26.6%), and falls or osteomyelitis (n=5, 6.3%). In 25 cases (31.6%) with adequate soft tissue and no active infection, 2.5–3 mm flexible intramedullary K-wires were used to guide the transported segment. The remaining 54 patients (69%) with active infection or poor soft tissue coverage were managed exclusively with external fixation. **Results:** Patients had undergone a mean of 2.8 prior failed surgical procedures (range: 1–16). The mean bone defect length was 9.3 cm (range: 5–18 cm). Infection eradication and bone union were successfully achieved in all 79 cases. The mean external fixation index was 1.3 months/cm. Bone results were excellent in 71 patients (89.9%), good in 5 (6.3%), fair in 2 (3.8%), and poor in 1 (1.3%). Functional results were excellent in 46 patients (58.2%), good in 28 (35.4%), and fair in 2 (3.8%), with no poor or failed outcomes reported. Skin invagination at the gap site occurred in 34 patients (43%), requiring surgical adjustment in 27 (34.2%); notably, such adjustments were unnecessary when intramedullary flexible K-nails were utilized. **Conclusion:** The Ilizarov technique is a highly effective solution for challenging tibial defects, allowing for the simultaneous resolution of bone loss, infection, nonunion, and soft tissue compromises. Furthermore, the adjunctive use of flexible intramedullary K-nails mitigates the need for subsequent docking site adjustments.

Keywords: Ilizarov Technique; Tibial Bone Defect; Nonunion; Tibial Bone Lengthening

1. Introduction

Tibial fractures complicated by extensive bone and soft tissue loss, or secondary bone defects resulting from infected nonunions, remain formidable challenges for orthopedic surgeons and are associated with significant long-term morbidity. While acute shortening of more than 4 cm is sometimes utilized, this approach can induce tortuous vasculature, resulting in a low-flow state with severe detrimental consequences. Furthermore, acute compression of open soft-tissue wounds can lead to tissue bunching, devascularization, significant edema, and an elevated risk of subsequent necrosis and infection [1-4].

Historically, the complexity of managing segmental long-bone defects often necessitated amputation; however, the clinical emphasis has progressively shifted toward limb salvage. As Keating *et al.* [5] noted, limb reconstruction in the presence of massive bone loss is technically demanding, time-intensive, and physically and psychologically exhausting for the patient, often yielding unpredictable outcomes. Successful reconstruction fundamentally requires an infection-free environment coupled with stable, reliable fixation.

Currently, a variety of surgical strategies are utilized to address these defects, including fibular grafts [6], free vascularized iliac crest grafts [7], tibiofibular synostosis [8], the Masquelet induced membrane technique [9], and distraction osteogenesis via bone transport [10-15]. The sheer diversity of these reconstructive methods underscores the inherent difficulty of achieving osseous union across extensive defect gaps. Consequently, the present study aims to evaluate the clinical efficacy of the Ilizarov technique in managing tibial nonunions complicated by segmental bone loss.

2. Patients and Method

This study utilizes a prospective cohort design reviewing patients in a multicenter study from 2004 to 2016, which was carried out at the orthopedic unit of Al Wahda Educational Hospital, Maabar, Thamar University, First Orthopedic and Plastic Hospital, Sana'a, and General Military Hospital, Sana'a, and informed consent was obtained from all patients. Out of 79 patients, 75 (94.9%) were male, and 4 (5.1%) were female.

The procedure is ethically sound when performed with appropriate medical and ethical standards. The institutional review board approval has been obtained from the ethics committee of each hospital included in our research. A written inform consent has been gotten from patients or their families.

Patients from either gender were included with an age range from 12 to 60 years, if they had a tibial bone defect of more than 5cm due to bone loss after trauma or debridement. Patients lost to follow-up, and those demanding premature fixator removal were excluded. The defect developed in 53 (67.1%) patients as a result of gunshot injury and in 21 (26.6%) patients as a result of traffic accidents, and 5 (6.3%) as a result of falling from height and osteomyelitis.

We defined primary bone loss as bone missing immediately at the time of injury and secondary bone loss as the bone defect resulting from subsequent surgical debridement. In our cohort, primary bone loss was present in 67.09% of patients, while secondary bone loss occurred in 32.91% of patients. Fractures were located in the distal third of the tibia in 41, 8 in the proximal third, and 30 were located in the middle third; thirty were on the right, and forty-nine were on the left lower extremity.

At presentation, a detailed history was obtained for the initial injury and previous surgical interventions. The patients were examined for the condition of soft tissue, presence of shortening, neurovascular deficiency, and active infection, if any, and the function of relevant joints was documented. Radiological evaluation was done to determine the fracture pattern, plane of deformity, alignment, and to look for signs of osteomyelitis.

At the time of surgery, in cases presenting with infected nonunion, the definitive bone defect size was measured intraoperatively after radical debridement and resection of all infected and non-viable bone segments. 36 (45.6%) tibial nonunions with bone defect or shortening were diagnosed as infected. Resection of all devitalized or sclerotic bone and fibrous tissue was removed from the site, leaving healthy, viable bone ends. The medulla was opened, and the defect was measured. In those cases, with a big defect (more than 10 cm), we used 2 flexible intramedullary nails or 2.5 mm K wires to guide the transported segment, and we didn't apply an intramedullary nail in cases of infection or poor soft tissue coverage. In case of bad skin cover, muscle-cutaneous flab is used to cover the anterior aspect of the leg. Soft tissue coverage was achieved using local rotational flaps, free microvascular flaps, or split-thickness skin grafting, depending on the wound requirements.

Data were analyzed for mean age, mean bone defects, mean follow-up, bone union, bone results, functional results, complications per patient, external fixation time, and external fixation index were recorded and statistically analyzed using weighted means based on the sample size in the study by SPSS software. Continuous variables were analyzed using the Student's t-test or Mann-Whitney U test, depending on normality. Categorical variables were compared using the Chi-square test or Fisher's exact test. A statistically significant difference was set at $P < 0.05$.

3. Management Protocol & Operative Technique

After completing pre-operative investigations, we performed a careful preparation that included assessment of the size of the bone defect, identification of the infecting microorganisms, and evaluation of the condition of both the adjacent soft tissue and the neighboring joints, as shown in Figure 1.

In infected cases, according to microbiological sensitivity tests, an appropriate antibiotic was selected and used until there were no clinical signs of acute infection (redness, swelling, or pus discharge). The patient is placed in the supine position on a radiolucent operating table. The injured leg is in position. Anesthesia is given. The site of the infected nonunion was exposed through a standard approach. Samples for culture and sensitivity were taken promptly to the laboratory and processed immediately.

Resection of all devitalized or sclerotic bone and fibrous tissue was removed from the site, leaving healthy, viable bone ends; the medulla was opened (Figure 2). If the fibula was intact, a resection was carried out between the fracture and osteotomy site, so that the lengthening could be done.

To decrease the operation time, an Ilizarov frame was constructed preoperatively according to the fracture and cortico- or osteotomy sites. For bone transport, the simplest, most commonly used configuration consists of three rings, with one proximal to the corticotomy site, one distal to the zone of the original defect, and one in the transport segment. Most of the time, we used an image intensifier to achieve reduction and near-normal alignment of the fracture. For each ring, a minimum of 2 wires was used.

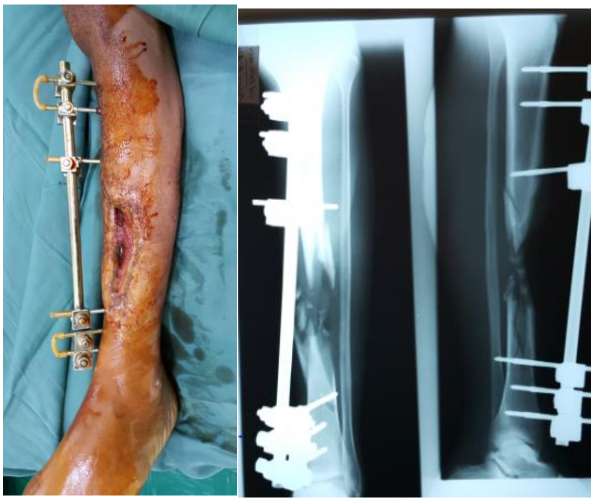

Figure 1: Preoperative clinical presentation and radiograph of a patient with a left tibial bone defect resulting from a gunshot injury, initially stabilized with a temporary external fixator.

Figure 2: Intraoperative clinical view following the removal of the temporary external fixator and the radical debridement of infected, devitalized bone and soft tissue.

While inserting the wires, they were first gently pushed up to the bone through the skin and then drilled with a power drill. As soon as they come out through the other cortex, they are gently hammered to get out to the other side. Muscles were at their maximum length while inserting the pins, and all the wires were passed through safe zones. All the wires were tensionized before fastening to rings, either with a wire tensioner or manually with spanners at both ends simultaneously on plain wires and only the opposite end on olive tip wires. A corticotomy is then performed using a Gigli saw from the posterior aspect and an osteotome from the medial and lateral aspects. At the end of the surgical procedure, the hemovac drain was routinely used. In cases with bad skin cover, muscle-cutaneous flab is used to cover the anterior aspect of the leg (was done in 2 cases).

In active infected cases, treatment was performed in two stages. In the first stage, an accurate *debridement* of the infected nonunion site, with bone end transverse resection until healthy bone was observed, and complete excision of the infected and necrotic soft tissues was performed, and cultures were taken. At this time, the Ilizarov apparatus was applied to the leg (Figure 3). We combined K-wires with Schanz pins to make the fixator more rigid and stable at the proximal and distal ends of the tibia, with only K-wires in the segment for transport to decrease deep lesions in soft tissues during transport. The assembly must be extended to the hind- and forefoot in patients in whom a loss of tissue in the distal tibia requires extensive resection, and the length of the distal tibial fragment is only a few centimeters in length, and if the bone defect is more than 5 cm, to prevent equins deformity.

Figure 3: Postoperative radiograph and clinical photograph demonstrating the application of the Ilizarov circular frame, utilizing flexible intramedullary K-wires as guides for the transported bone segment.

By the end of the distraction phase, the part of the device that is in the forefoot was removed. When the infection had subsided and the wound was healed, the second step consisted of performing a corticotomy at the proximal or distal tibial metaphysis according to the resection site, distal or proximal (Figure 4).

Figure 4: Radiographic and clinical appearance after the distraction osteogenesis phase, illustrating the transit of the bone segment and the developing regenerated bone.

In the noninfected cases, *debridement* and corticotomy were performed in one step with two 2.5 mm K-wires intramedullary to guide the segment of transport. After a delay of 5 to 10 days, distraction is begun by turning the nuts on the metal rods 0.5mm, two times per day, for a total distraction of 1mm per day. Knee and ankle kinesitherapy and muscle strengthening are started immediately, and standing and walking start a few days after the operation.

Patients were initially followed every 2 weeks till the lengthening was completed, and thereafter monthly till the consolidation of the regenerate. Once bone ends were in near apposition, a docking procedure was performed as necessary. Compression over the docking site was maintained by ¼ turn 2x/week.

In our study, the bone ends at the defect site were cut in a transverse manner at the primary debridement or at the time of adjustment or docking site procedure, to make a maximal contact area when the transported segment comes into contact with the other fragment, and to avoid bone graft as shown in Figure 5.

Figure 5: Final clinical and radiographic outcomes demonstrating complete consolidation at the docking site, mature regenerated bone calcification, and restoration of limb alignment following the removal of the Ilizarov frame.

Once the distraction is stopped, the frame remains attached to allow the new bone to harden. Dynamization was performed in all cases before the removal of the frame. This time is usually one month per cm of new bone formed. After this time the fixator removal was performed either in the Outpatient Department (OPD) without anesthesia for cooperative patients with stable clinical signs, or in the Operating Room (OR) under General Anesthesia (GA). GA was strictly reserved for pediatric patients, highly anxious individuals, or cases requiring significant pin tract debridement.

4. Results

The clinical outcomes of the 79 patients were evaluated following a mean of 2.8 prior failed surgical procedures (range: 0–16). The mean length of the tibial bone defect was 9.3 cm (range: 5–16 cm). Infection was successfully eradicated in all 37 cases presenting with infected nonunion. Furthermore, definitive bone union was achieved in all 79 patients. The mean external fixation index was 1.3 months/cm. Statistical analysis revealed no significant difference in the external fixation index between infected and non-infected cases (P = 0.630), as detailed in Table 1.

Table 1. Association Between Infected and Non-Infected Cases Regarding External Fixation Index

Status	Mean Time for Frame Removal (Days)	Standard Deviation (SD)	P-value
Infected	347	85.5	0.630
Non-Infected	359	124.9	

Note to typesetter: The P-value applies to the comparison between the two groups

Outcomes were classified using the Association for the Study and Application of the Method of Ilizarov (ASAMI) scoring system [16]. Bone results were categorized as excellent in 68 patients (86.1%), good in 6 (7.6%), fair in 1 (1.3%), and poor in 4 (5.1%) (Table 2). Functional results were excellent in 46 patients (58.2%), good in 28 (35.4%), and fair in 5 (6.3%). Notably, there were no patients with poor functional results or total failure (Table 3).

All the patients had achieved consolidation of the regenerate at the distracted site before union at the compression site, even those whom acute compression at the fracture site, followed by lengthening.

Table 2. Evaluation of the bony results using the ASAMI scoring system (n = 79) [16].

Bone results	No. of patients	%	Criteria
Excellent	68	86.08	Union, no infection, deformity < 7°, limb length discrepancy (LLD) < 2.5 cm
Good	6	7.59	Union plus any two of the following: absence of infection, deformity < 7°, LLD < 2.5 cm.
Fair	1	1.27	Union plus any one of the following: absence of infection, deformity < 7°, LLD < 2.5 cm.
Poor	4	5.06	Nonunion/refracture/union plus infection plus deformity > 7° plus LLD > 2.5 cm

Table 3. Evaluation of the functional results using the ASAMI scoring system (n = 79)

Functional results	No. of patients	%	Criteria
Excellent	46	58.23	Active, no limp, minimum stiffness (loss of < 15° knee extension/< 15° ankle dorsiflexion), no reflex sympathetic dystrophy (RSD), insignificant pain.
Good	28	35.44	Active, with one or two of the following: limp, stiffness, RSD, significant pain
Fair	5	6.33	Active, with three or all of the following: limp, stiffness, RSD, significant pain
Poor	0	0	Inactive (unemployment or inability to return to daily activities because of injury)
Failure	0	0	Amputation

There was no relation between the infected and non-infected cases for the external fixator index (P > 0.05).

Complications were divided into problems, obstacles, and true complications according to a system proposed by Paley [17] (Table 4). Problems are difficulties encountered while the fixator is still in place (distraction and consolidation period) and are resolved without operative treatment. Obstacles are complications encountered while the fixator is in place and are resolved by operative treatment. True complications are those that arise after the removal of the fixator and resolved operative treatment.

Table 4. Complications Encountered During and After Treatment.

Problems	Obstacles	True Complications
1. Pain during the distraction period 41/79 2. Infection at the regenerate site 2/79 3. Pin tract infection – 79/79 4. Infected at the regenerate site - 2/79 5. Knee Contracture – 1/79 6. Angulation of fragments – 5/79	1. Insufficient regeneration – 2/79 2. Premature Ossification of regenerate bone – 4/79 3. Skin invagination over gap site – 34/79 4. Adjustment was done in 27/79. 5. Bone graft -1/79	1. Equines deformity – 2/79 2. Refracture – 3/79

Premature ossification of the corticotomy site occurred in four patients. These were all treated by repeat corticotomy. Skin invagination over the gap site was seen in thirty-four (43%) patients, all of whom had big bone defects. All were resolved by a docking procedure, which necessitated removal of fibrous tissue from the gap site and adjustment of the bone ends if necessary.

A bone graft was performed in one case. Adjustment was done in 27 (34.2%) patients. Refracture at the docking site, which occurred after the removal of the fixator, was noted in 3 (3.8%) cases, two of which were managed by cast for three months, and the third was managed by reapplication of the Ilizarov apparatus after refreshment of the fracture site, and it was removed after 5 months. Achilles tendon lengthening for equinus deformity was performed in one patient. Pin tract infection was the most common complication. All the patients had a feeling of pain during the distraction period and required oral analgesics.

A total of 41 patients who required lengthening of more than 5 cm complained of pain during distraction, especially at the knee joint and at the site of the K-wires near the docking site. This was treated with analgesia (acetaminophen-codeine combination) as necessary or to divide distraction into times or four times. No neurovascular problems were caused by either intraoperative pin insertion. No patient developed compartment syndrome. Invagination was noted in 34 (43%) cases, bone graft was performed in one case. Adjustment was done in 27 (34.2%) patients.

The Ilizarov External Fixator (IEF) provides sufficient stability and beneficial cyclical axial loading and minimizes shear forces, all of which are important for fracture healing. The axial deviation during bone transport occurred in 27 patients and frame adjustments for modification were performed in these patients.

5. Discussion

Most authors reported that although the autogenous bone grafts, allografts, bone graft substitutes, and vascularized fibular bone grafts are effective in the treatment of selected long bone nonunions with defects, these techniques have their limitations. Tibial nonunion with a bone defect is usually not an isolated problem. It may be associated with infection, shortening, soft tissue dystrophy, disuse osteoporosis, equinus deformity, angular deformity, and neurovascular damage. Joshi and Kostakis [18] and Li *et al.,* [19] reported that a conventional autogenous bone grafting has limitations for the treatment of large defects, the time-period for graft incorporation is prolonged, and the quantity of available autogenous graft is limited, as well as producing significant donor site morbidity, late stress fracture, and nonunion at the graft site, blood loss, and paraesthesia [18-21], superficial infection [20, 22-24], hematoma [18, 25], poor cosmesis [20, 26] and most commonly, acute or chronic donor site pain [18-20, 22-24, 26-30]. Moreover, Toh and Jupiter [31] and Corona *et al.* [32] believed that in an infected defect, scarring of the soft-tissue envelope compromises revascularization of the graft.

Also, Ziran *et al.* [33] supported that the use of AlloMatrix/demineralized bone matrix as an alternative for autogenous bone graft in the treatment of nonunions resulted in an unacceptably high rate of complications, especially if there is a large volumetric defect or a history of any prior contamination of the tissue bed.

Most authors believe that a free vascularized fibula grafting is technically challenging and confers its own set of inherent risks and potential complications. Adequate hypertrophy of the incorporated fibular graft may take several years, and prolonged bracing, problems with union, as well as fatigue/stress fracture are common, which range between 10% and 25% [34-39]. Furthermore, donor site morbidity has been well documented, and up to 10% of patients may subsequently develop ankle pain, instability, and/or progressive valgus deformity if fibula harvest is not performed with proper technique [34, 40, 41].

In our study, the mean external fixation index was 1.3 months/cm, and the complications per patient were 2.6. The first data were better than the average data that were recorded in the literature, but the complication rate per patient was higher. Excellent rate in bone results was 86.1%, and good 7.6%, and excellent rate in functional results was 58.2%, meanwhile, good 35.4% in our study; these data were also better than the average data that was recorded in the literature. This current study reports an average defect of 9.4 centimeters (5 – 17 cm) as listed in Table 5.

Lavini *et al.* [42] performed application of the technique of acute compression and lengthening was performed only in two patients, and both patients had developed pus formation at the site of compression, which we explain as due to soft tissue stacking. So, it was limited to the extent of bone defects. Although acute compression beyond 4-5 cm could cause overmuch soft tissue stacking and arteriolar occlusion, which could affect new bone formation and the healing of fracture ends. Magadum *et al.* [43] represented in their literature, a huge bone defects (mean 10 cm, maximum 17 cm) were treated successfully by acute compression and distraction.

Bone transport could achieve good results in the treatment of both small and massive bone defects [44-48]. So, bone transport has no limit for the extent of bone defects, and it gives the surgeon the confidence to remove as much bone as necessary to ensure complete removal of pathologic bone. We achieved not only filling the bone defect and nonunion, but also the eradication of infection in all 37 cases. Green [49] proved that, as Ilizarov is often quoted, "osteomyelitis burns in the flames of the regenerate". Sveshnikov *et al.* [50] found that the vascularity is noted to increase in the vicinity of the corticotomy site. This neovascularization promotes healing and also helps eradicate infection. Green *et al.* [51] conducted that wound breakdown, invagination, pin-track infection, skin invagination, and axial deviation were common complications in the course of bone transport. Soft tissue interposition also prevents compression and new bone formation at the docking site.

Table 5. Comparison of Clinical Outcomes in Established Bone-Transport Studies.

Reference	Number of patients	Mean of bone loss (cm)	External fixator index (months/cm)	Complication rate per patient
Sen *et al.* [52]	17	5.6	1.4	1.2
Atesalp *et al.* [53]	43	9.7	1.4	1.1
Cattaneo *et al.* [54]	28	4.0	2.2	0.6
Green *et al.* [51]	17	5.1	1.9	3.5
Zorn & Iii [55]	21	6.5	2.6	1,4
Biermann *et al.* [10]	25	4.1	2.1	2.1
Saleh & Rees [56]	8	6.5	2.5	2.2
Dendrinos *et al.* [57]	28	6.0	1.7	2.5
Polyzois *et al.* [58]	42	6.0	1.6	1.4
Song *et al.* [11]	27	8.3	1.0	0.5
Paley & Maar [15]	19	10.0	1.6	2.9
Yin *et al.* [59]	66	6.27	1.38	1.08
Present Study	**79**	**9.3**	**1.3**	**2.6**

Our study adopts regular adjustment and skin elevation at the docking site, and we have noted shortening of the time for healing at the docking site. The external fixator index was 1.3 cm/month. During adjustment, elevation of the skin due to invagination and docking site procedure, we had noted not only an increase in the vascularity at the bone ends, but also the medullary canal at both ends became close, and the shape becomes difference comparison with the initial shape after resection at the first operation. We think that after the last procedures, we refresh both ends and perform multiple drilling, opening the medullary canal if possible, and continue compression, and we achieve healing in a good position and faster than without these procedures. We avoid the necessity for a bone graft. The only case where a bone graft was done was due to healing at the docking site with a diameter less than half the diameter of the bone after prematurity of the regenerate.

If the contact area at the docking site is small, bone grafting will be necessary [11, 56, 60-63]. Several studies have reported that 80 to 100% Song *et al.* [11], Schultz *et al.* [64], 10% Thirumal and Shong [60], and 50% Maini *et al.* [61] of cases have required bone grafting at the docking site. The leading edge of the transported segment is relatively avascular. Green *et al.* [51] and Paley *et al.* [15] reported that this can delay union, unless the sclerotic end is trimmed, and 50% of patients reportedly undergo debridement of the leading edge of the transported segment.

In our study, most of the bone defects were due to high-energy trauma 93.7% (gunshot and RTA 67.1% and 26.6% respectively), open fractures were 84.8%, the distal third was involved 51.9%, the middle 38.05 whereas the proximal third was involved only in 10.1% only and this fact is due to poor soft tissue at the distal part of the leg.

Ilizarov technique studies reported that most complications were related to the docking site, such as nonunion, delayed union, malalignment, low cross-sectional area, and soft-tissue invagination [15, 16, 51, 55, 65-67]. Despite the many complications, the Ilizarov method has shown its versatility and reliability in the treatment of cases with problematic bone defects, infection, shortening, nonunions, complex trauma, and deformities.

The initial treatment by AO external fixation was in 59 (74.7 %) cases, to stabilize the injured segment of the limb with minimal additional trauma, avoiding introducing foreign bodies in the damage zone. Moreover, one-planer of the external fixation practically doesn't restrict surgical access to an injured limb and doesn't disturb further closure of skin defects. Simplicity of the application, less traumatic methods of external fixation, and relatively short duration of the operation are significant for patients with multiple traumas and in cases of mass hospitalization.

Only primary fixation by the Ilizarov technique was applied in 8 (10.1%) cases. 12 (15.2%) cases as a sequel of infection after open reduction and internal fixation by plates or due to osteomyelitis. The need for distraction osteogenesis due to bone defects was most frequent in young adults (21–40 years).

Ilizarov bone transport is an effective salvage tool in obtaining union in patients with an infected nonunion and as a primary tool in patients with large segmental bone loss due to trauma. The lengthy treatment time and considerable number of complications must be fully understood by both the surgeon and the patient prior to undertaking this complex treatment process.

6. Conclusion

The Ilizarov technique remains a highly effective and versatile modality for managing complex tibial defects. It uniquely enables the simultaneous resolution of massive segmental bone loss, active infection, nonunion, and compromised soft tissue envelopes. Furthermore, the adjunctive use of flexible intramedullary K-wires significantly mitigates the need for subsequent surgical adjustments at the docking site. Crucially, the empirical outcomes of this study demonstrate that the initial presence of active infection does not adversely affect the external fixation index or the overall success of bone transport when utilizing this protocol.

Ethical Approval

This study was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki. Ethical approval was obtained from the Medical Ethics Committee of the Faculty of Medicine, Thamar University, Yemen (Approval No.: TUMEC-223), level 1.

Patient Consent

Written informed consent was obtained from all patients prior to their enrollment and surgical intervention. Because the study cohort included adolescent participants (ages ranging from 12 to 60 years), written informed consent for patients under the age of 18 was strictly obtained from their parents or legal guardians. Patient confidentiality and data anonymity were maintained throughout the entirety of the study.

Data Availability

The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

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Conflict of Interest

The authors declare no conflicts of interest.

References

[1] Kocialkowski, A., Marsh, D.R., Shackley, D.C. (1998) Closure of the skin defect overlying infected non-union by skin traction, *British Journal of Plastic Surgery* **51**: 307-310.

[2] Lenoble, E., Lewertowski, J.M., Goutallier, D. (1995) Reconstruction of Compound Tibial and Soft Tissue Loss Using a Traction Histogenesis Technique, *Journal of Trauma and Acute Care Surgery* **39**: 356-360.

[3] Kesemenli, C., Subasi, M., Kirkgoz, T., Kapukaya, A., Arslan, H. (2001) Treatment of Traumatic Bone Defects by Bone Transport, *Acta Orthopaedica Belgica* **67**: 380-386.

[4] Mahaluxmivala, J., Nadarajah, R., Allen, P.W., Hill, R.A. (2005) Ilizarov external fixator: acute shortening and lengthening versus bone transport in the management of tibial non-unions, *Injury* **36**: 662-668.

[5] Keating, J.F., Simpson, A.H.R.W., Robinson, C.M. (2005) The management of fractures with bone loss, *The Journal of Bone & Joint Surgery British Volume* **87-B**: 142-150.

[6] El-Gammal, T.A., Shiha, A.E., El-Deen, M.A., El-Sayed, A., Kotb, M.M., Addosooki, A.I., Ragheb, Y.F., Saleh, W.R. (2008) Management of traumatic tibial defects using free vascularized fibula or Ilizarov bone transport: A comparative study, *Microsurgery* **28**: 339-346.

[7] Tonoli, C., Bechara, A.H.S., Rossanez, R., Belangero, W.D., Livani, B. (2013) Use of the Vascularized Iliac-Crest Flap in Musculoskeletal Lesions, *BioMed Research International* **2013**: 237146.

[8] Ebraheim, N.A., Haman, S.P., Sabry, F.F., Emara, K. (2005) Tibiofibular synostosis procedure in the management of complex tibia fractures, *American Journal of Orthopedics (Belle Mead, N.J.)* **34**: 493-497.

[9] Masquelet, A.C. (2003) Muscle reconstruction in reconstructive surgery: soft tissue repair and long bone reconstruction, *Langenbeck's Archives of Surgery* **388**: 344-346.

[10] Biermann, J., Prokuski, L., Marsh, J. (1994) Chronic Infected Tibia1 Nonunions With Bone Loss Conventional Techniques Versus Bone Transport, *Clinical Orthopaedics & Related Research* **301**: 139-146.

[11] Song, H.R., Cho, S.H., Koo, K.H., Jeong, S.T., Park, Y.J., Ko, J.H. (1998) Tibial bone defects treated by internal bone transport using the Ilizarov method, *International Orthopaedics* **22**: 293-297.

[12] Rigal, S., Tripon, P. (2005) Traitement des pertes de substance osseuse traumatiques des diaphyses par transport osseux segmentaire, *Annales Orthopédiques de l'Ouest* **37**: 163-5.

[13] Ilizarov, S., Katz, H., Freudigman, P., Tracey Watson, J., Weitzman, A., Robert Rozbruch, S. (2006) Simultaneous Treatment of Tibial Bone and Soft-tissue Defects With the Ilizarov Method, *Journal of Orthopaedic Trauma* **20**: 194-202.

[14] Trigui, M., Ayadi, K., Ellouze, Z., Gdoura, F., Zribi, M., Keskes, H. (2008) Treatment of bone loss in limbs by bone transport, *Revue de chirurgie orthopedique et reparatrice de l'appareil moteur* **94**: 628-634.

[15] Paley, D., Maar, D.C. (2000) Ilizarov bone transport treatment for tibial defects, *Journal of Orthopaedic Trauma* **14**: 76-85.

[16] Paley, D., Catagni, M.A., Argnani, F., Villa, A., Bijnedetti, G.B., Cattaneo, R. (1989) Ilizarov Treatment of Tibial Nonunions With Bone Loss, *Clinical Orthopaedics and Related Research* **241**: 146-165.

[17] Paley, D. (1990) Problems, obstacles, and complications of limb lengthening by the Ilizarov technique, *Clinical Orthopaedics and Related Research* **250**: 81-104.

[18] Joshi, A., Kostakis, G.C. (2004) An investigation of post-operative morbidity following iliac crest graft harvesting, *British Dental Journal* **196**: 167-171.

[19] Li, Y., Shen, S., Xiao, Q., Wang, G., Yang, H., Zhao, H., Shu, B., Zhuo, N. (2020) Efficacy comparison of double-level and single-level bone transport with Orthofix fixator for treatment of tibia fracture with massive bone defects, *International Orthopaedics* **44**: 957-963.

[20] Schnee, C.L., Freese, A., Weil, R.J., Marcotte, P.J. (1997) Analysis of Harvest Morbidity and Radiographic Outcome Using Autograft for Anterior Cervical Fusion, *Spine* **22**: 2222-2227.

[21] Nkenke, E., Weisbach, V., Winckler, E., Kessler, P., Schultze-Mosgau, S., Wiltfang, J., Neukam, F.W. (2004) Morbidity of harvesting of bone grafts from the iliac crest for preprosthetic augmentation procedures: A prospective study, *International Journal of Oral and Maxillofacial Surgery* **33**: 157-163.

[22] Skaggs, D.L., Samuelson, M.A., Hale, J.M., Kay, R.M., Tolo, V.T. (2000) Complications of Posterior Iliac Crest Bone Grafting in Spine Surgery in Children, *Spine* **25**: 2400-2402.

[23] Swan, M.C., Goodacre, T.E.E. (2006) Morbidity at the iliac crest donor site following bone grafting of the cleft alveolus, *British Journal of Oral and Maxillofacial Surgery* **44**: 129-133.

[24] Robertson, P.A., Wray, A.C. (2001) Natural History of Posterior Iliac Crest Bone Graft Donation for Spinal Surgery: A Prospective Analysis of Morbidity, *Spine* **26**: 1473-1476.

[25] Westrich, G.H., Geller, D.S., O'Malley, M.J., Deland, J.T., Helfet, D.L. (2001) Anterior Iliac Crest Bone Graft Harvesting Using the Corticocancellous Reamer System, *Journal of Orthopaedic Trauma* **15**: 500-506.

[26] Hill, N.M., Geoffrey Horne, J., Devane, P.A. (1999) Donor Site Morbidity in the Iliac Crest Bone Graft, *Australian and New Zealand Journal of Surgery* **69**: 726-728.

[27] Silber, J.S., Anderson, D.G., Daffner, S.D., Brislin, B.T., Leland, J.M., Hilibrand, A.S., Vaccaro, A.R., Albert, T.J. (2003) Donor Site Morbidity After Anterior Iliac Crest Bone Harvest for Single-Level Anterior Cervical Discectomy and Fusion, *Spine* **28**: 134-139.

[28] Sasso, R.C., LeHuec, J.C., Shaffrey, C., The Spine Interbody Research Group (2005) Iliac Crest Bone Graft Donor Site Pain After Anterior Lumbar Interbody Fusion: A Prospective Patient Satisfaction Outcome Assessment, *Clinical Spine Surgery* **18**: S77-S81.

[29] Kager, A.N., Marks, M., Bastrom, T., Newton, P.O. (2006) Morbidity of Iliac Crest Bone Graft Harvesting in Adolescent Deformity Surgery, *Journal of Pediatric Orthopaedics* **26**: 132-134.

[30] Heary, R.F., Schlenk, R.P., Sacchieri, T.A., Barone, D., Brotea, C. (2002) Persistent iliac crest donor site pain: independent outcome assessment, *Neurosurgery* **50**: 510-517.

[31] Toh, C.L., Jupiter, J.B. (1995) The Infected Nonunion of the Tibia, *Clinical Orthopaedics and Related Research* **315**: 176-191.

[32] Corona, P.S., Pujol, O., Vicente, M., Ricou, E., de Albert, M., Maestre Cano, D., Salcedo Cánovas, C., Martínez Ros, J. (2022) Outcomes of two circular external fixation systems in the definitive treatment of acute tibial fracture related infections, *Injury* **53**: 3438-3445.

[33] Ziran, B.H., Smith, W.R., Morgan, S.J. (2007) Use of Calcium-Based Demineralized Bone Matrix/Allograft for Nonunions and Posttraumatic Reconstruction of the Appendicular Skeleton: Preliminary Results and Complications, *Journal of Trauma and Acute Care Surgery* **63**: 1324-1328.

[34] Hariri, A., Mascard, E., Atlan, F., Germain, M.A., Heming, N., Dubousset, J.F., Wicart, P. (2010) Free vascularised fibular graft for reconstruction of defects of the lower limb after resection of tumour, *The Journal of Bone & Joint Surgery British Volume* **92-B**: 1574-1579.

[35] Wood, M.B. (2007) Free Vascularized Fibular Grafting—25 Years' Experience: Tips, Techniques, and Pearls, *Orthopedic Clinics of North America* **38**: 1-12.

[36] Chen, C.M., Disa, J.J., Lee, H.-Y., Mehrara, B.J., Hu, Q.-Y., Nathan, S., Boland, P., Healey, J., Cordeiro, P.G. (2007) Reconstruction of Extremity Long Bone Defects after Sarcoma Resection with Vascularized Fibula Flaps: A 10-Year Review, *Plastic and Reconstructive Surgery* **119**: 915-924.

[37] McClure, P.K., Abouei, M., Conway, J.D. (2021) Reconstructive Options for Tibial Bone Defects, *JAAOS - Journal of the American Academy of Orthopaedic Surgeons* **29**: 901-909.

[38] Chang, D.W., Weber, K.L. (2005) Use of a Vascularized Fibula Bone Flap and Intercalary Allograft for Diaphyseal Reconstruction after Resection of Primary Extremity Bone Sarcomas, *Plastic and Reconstructive Surgery* **116**: 1918-1925.

[39] Minami, A., Kasashima, T., Iwasaki, N., Kato, H., Kaneda, K. (2000) Vascularised fibular grafts, *The Journal of Bone & Joint Surgery British Volume* **82-B**: 1022-1025.

[40] Vail, T.P., Urbaniak, J.R. (1996) Donor-Site Morbidity with Use of Vascularized Autogenous Fibular Grafts, *The Journal of Bone & Joint Surgery British Volume* **78**: 204-11.

[41] Kanaya, K., Wada, T., Kura, H., Yamashita, T., Usui, M., Ishii, S. (2002) Valgus deformity of the ankle following harvesting of a vascularized fibular graft in children, *Journal of Reconstructive Microsurgery* **18**: 091-096.

[42] Lavini, F., Dall'Oca, C., Bartolozzi, P. (2010) Bone transport and compression-distraction in the treatment of bone loss of the lower limbs, *Injury* **41**: 1191-1195.

[43] Magadum, M., Yadav, C.B., Phaneesha, M., Ramesh, L. (2006) Acute compression and lengthening by the Ilizarov technique for infected nonunion of the tibia with large bone defects, *Journal of Orthopaedic Surgery* **14**: 273-279.

[44] Shetu, N.H., Balo, N.R., Rahaman, M.S., Mahmud, B.R., Islam, M.O. (2025) Clinical Outcomes of Bone Transport Over Intramedullary Nail by Ilizarov Method, *Scholars Journal of Applied Medical Sciences* **13**: 377-385.

[45] Abdel-Aal, A.M. (2006) Ilizarov bone transport for massive tibial bone defects, *Orthopedics* **29**: 70.

[46] Liu, T., Yu, X., Zhang, X., Li, Z., Zeng, W. (2012) One-stage management of post-traumatic tibial infected nonunion using bone transport after debridement, *Turkish Journal of Medical Sciences* **42**: 1111-1120.

[47] Xu, Y.-Q., Fan, X.-Y., He, X.-Q., Wen, H.-J. (2021) Reconstruction of massive tibial bone and soft tissue defects by trifocal bone transport combined with soft tissue distraction: experience from 31 cases, *BMC Musculoskeletal Disorders* **22**: 34.

[48] Bumbaširević, M., Tomić, S., Lešić, A., Milošević, I., Atkinson, H.D.E. (2010) War-related infected tibial nonunion with bone and soft-tissue loss treated with bone transport using the Ilizarov method, *Archives of Orthopaedic and Trauma Surgery* **130**: 739-749.

[49] Green, S.A. (1991) Osteomyelitis. The Ilizarov perspective, *The Orthopedic Clinics of North America* **22**: 515-521.

[50] Svesnikov, A., Barabash, A., Cheplenko, T., Smotrova, L., Larionov, A. (1984) Radionuclide studies of osteogenesis and circulation in substitution of large defects of the leg bones in experiment, *Ortopediia, Travmatologiia i Protezirovanie* 33-37.

[51] Green, S.A., Jackson, J.M., Wall, D.M., Marinow, H., Ishkanian, J. (1992) Management of Segmental Defects by the Ilizarov Intercalary Bone

Transport Method, *Clinical Orthopaedics and Related Research* **280**: 136-142.

[52] Sen, C., Eralp, L., Gunes, T., Erdem, M., Ozden, V.E., Kocaoglu, M. (2006) An alternative method for the treatment of nonunion of the tibia with bone loss, *The Journal of Bone & Joint Surgery British Volume* **88-B**: 783-789.

[53] Atesalp, A.S., Basbozkurt, M., Erler, K., Sehirlionğlu, A., Tunay, S., Solakoğlu, C., Gür, E. (1998) Treatment of tibial bone defects with the Ilizarov circular external fixator in high-velocity gunshot wounds, *International Orthopaedics* **22**: 343-347.

[54] Cattaneo, R., Catagni, M., Johnson, E.E. (1992) The Treatment of Infected Nonunions and Segmental Defects of the Tibia by the Methods of Ilizarov, *Clinical Orthopaedics and Related Research* **280**: 143-152.

[55] Zorn, K., Iii, G. (1994) Segmental Tibia1 Defects Comparing Conventional and Ilizarov Methodologies, *Clinical Orthopaedics & Related Research* **301**: 118-123.

[56] Saleh, M., Rees, A. (1995) Bifocal surgery for deformity and bone loss after lower-limb fractures. Comparison of bone-transport and compression-distraction methods, *The Journal of Bone & Joint Surgery British Volume* **77-B**: 429-434.

[57] Dendrinos, G.K., Kontos, S., Lyritsis, E. (1995) Use of the Ilizarov technique for treatment of non-union of the tibia associated with infection, *The Journal of Bone & Joint Surgery British Volume* **77**: 835-846.

[58] Polyzois, D., Papachristou, G., Kotsiopoulos, K., Plessas, S. (1997) Treatment of tibial and femoral bone loss by distraction osteogenesis, *Acta Orthopaedica Scandinavica* **68**: 84-88.

[59] Yin, P., Zhang, Q., Mao, Z., Li, T., Zhang, L., Tang, P. (2014) The treatment of infected tibial nonunion by bone transport using the Ilizarov external fixator and a systematic review of infected tibial nonunion treated by Ilizarov methods, *Acta Orthopaedica Belgica* **80**: 426-435.

[60] Thirumal, M., Shong, H.K. (2001) Bone transport in the management of fractures of the tibia, *The Medical Journal of Malaysia* **56**: 44-52.

[61] Maini, L., Chadha, M., Vishwanath, J., Kapoor, S., Mehtani, A., Dhaon, B.K. (2000) The Ilizarov method in infected nonunion of fractures, *Injury* **31**: 509-517.

[62] Ring, D., Jupiter, J.B., Gan, B.S., Israeli, R., Yaremchuk, M.J. (1999) Infected Nonunion of the Tibia, *Clinical Orthopaedics and Related Research* **369**: 302-311.

[63] Li, R., Zhu, G., Chen, C., Chen, Y., Ren, G. (2020) Bone Transport for Treatment of Traumatic Composite Tibial Bone and Soft Tissue Defects: Any Specific Needs besides the Ilizarov Technique?, *BioMed Research International* **2020**: 2716547.

[64] Schultz, J.H., Schmidt, H.G., Jürgens, C., Kortmann, H.R. (1994) Change in the treatment method of infected pseudarthrosis with bone loss of the tibia, *Zentralblatt fur Chirurgie* **119**: 714-721.

[65] Aronson, J. (1997) Current Concepts Review - Limb-Lengthening, Skeletal Reconstruction, and Bone Transport with the Ilizarov Method, *The Journal of Bone & Joint Surgery British Volume* **79**: 1243-58.

[66] Miraj, F., Nugroho, A., Dalitan, I.M., Setyarani, M. (2021) The efficacy of ilizarov method for management of long tibial bone and soft tissue defect, *Annals of Medicine and Surgery* **68**: 102645.

[67] Hernández-Irizarry, R., Quinnan, S.M., Reid, J.S., Toney, C.B., Rozbruch, S.R., Lezak, B., Fragomen, A.T. (2021) Intentional Temporary Limb Deformation for Closure of Soft-Tissue Defects in Open Tibial Fractures, *Journal of Orthopaedic Trauma* **35**: e189-e194.