

Ilizarov Circular Fixation for High-Velocity Firearm Injuries Causing High-Energy Tibial Fractures: A Prospective Cohort Study

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ABSTRACT

High-velocity gunshot tibial fractures present major reconstructive challenges owing to extensive contamination, soft-tissue devitalisation, and segmental bone loss that render early internal fixation hazardous. We aimed to document outcomes of a structured Ilizarov-based protocol for this injury type and describe a reproducible treatment framework for resource-constrained settings. Between January 2019 and December 2023, we prospectively enrolled 20 adult male patients with open tibial fractures from high-velocity firearm injuries at three Cairo trauma centres; all were treated definitively with an Ilizarov circular external fixator, with distraction osteogenesis and fibular autografting were employed selectively for segmental bone loss. The primary outcome was fracture union rate; secondary outcomes included fixation duration, surgical burden, and complications. Mean age was 29.7 ± 8.4 years. Fourteen fractures (70%) were Gustilo-Anderson type IIIA and six (30%) type IIIB; bone defects were present in 50% after debridement. Union was achieved in 19 of 20 patients (95%), and the single non-union resolved after frame revision and supplementary grafting. Mean fixation duration was 12.3 ± 7.28 months. Superficial pin-tract infection (Checketts-Otterburn Grade 1 or 2) occurred in 17 patients (85%) and deep surgical site infection in one (5%); ankle stiffness, axial malalignment, and limb length discrepancy each affected a minority of patients. A structured Ilizarov protocol can reliably achieve union in Gustilo type III gunshot tibial fractures with an acceptable complication profile; these findings are descriptive and do not establish superiority over alternative fixation strategies but support the Ilizarov circular frame as a suitable option for high-grade contaminated injuries in resource-limited environments.

Keywords: Ilizarov technique, tibial fractures, gunshot wounds, external fixators, bone transport.

INTRODUCTION

Across the world, firearm-related trauma continues to rise as both a military and civilian health problem. Gunshot wounds now rank second among injury-related causes of death and disability in young adults globally^{1,2}.

The tibia, owing to its subcutaneous course and limited soft-tissue envelope, experiences a disproportionate impact. Fractures arise in diverse contexts such as armed conflict, criminal violence, hunting accidents, and inadvertent discharge, and their management demands a clear understanding of projectile ballistics².

High-velocity rounds, generally defined as those travelling above 600 m/s, create a transient cavitation zone far exceeding the bullet track, stripping periosteum and devitalising muscle in ways that are

not always apparent on initial inspection³. The zone of injury invariably exceeds what the wound suggests, with direct implications for the aggressiveness of debridement required. The tibia's end-arterial blood supply, thin soft-tissue envelope, and periosteal vulnerability to stripping classify most high-velocity fractures as Gustilo-Anderson type III injuries, placing the limb at genuine risk of deep infection, non-union, and amputation if management is mishandled^{4,6}.

Contemporary practice mandates meticulous debridement, prompt skeletal stabilisation, and early definitive soft-tissue coverage⁴. Intramedullary nailing, the standard for lower-grade open tibial fractures, carries an unacceptably elevated risk of deep sepsis in high-grade injuries with delayed presentation, heavy bacterial loading, or significant osseous deficiency⁶.

The Ilizarov circular frame sidesteps many of these risks: applied remote from the zone of injury,

it stabilises the fracture, permits progressive bone transport for segmental defects, and leaves wounds fully accessible for staged debridement and soft-tissue reconstruction^{5,7,8}. Its known disadvantages are technical demand, months of patient commitment, and near-universal pin-tract infection, which are well documented but manageable^{7,8}.

Despite a sizeable body of retrospective literature, prospective data focusing specifically on high-velocity gunshot injuries treated with a clearly defined, reproducible protocol remain scarce, particularly from centres where delayed presentation and resource constraints are the norm⁹. Over five years and across three Cairo trauma centres, we prospectively followed 20 consecutive patients through a defined Ilizarov-based management algorithm, documenting outcomes and offering our protocol as a reproducible starting point for surgeons working in comparable environments.

MATERIALS AND METHODS

Study design and setting

This prospective cohort study was conducted from January 2019 to December 2023 at Ain Shams University Hospitals, El-Maadi Military Hospital, and Al-Helmia Military Hospital — three tertiary trauma institutions in Cairo, Egypt. Ethical approval was granted by the Ain Shams University Faculty of Medicine Ethics Committee (reference: FWA 00017585), and all participants provided written informed consent. The work adhered to the Declaration of Helsinki. This manuscript was prepared in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines for cohort studies.

Patient selection

Adults aged 18–60 years with open tibial fractures from confirmed high-velocity firearm injuries, an intact distal neurovascular examination, and fractures involving the tibial diaphysis or metaphysis (with or without intra-articular extension) were eligible. Exclusion criteria were: concurrent vascular injury requiring repair, significant peripheral nerve lesion, or a soft-tissue defect necessitating free or pedicled flap reconstruction. Over the five-year recruitment window, 20 patients satisfied all criteria and were enrolled.

Preoperative assessment and initial management

Patients were admitted within 48 hours of injury and were managed under the Advanced Trauma

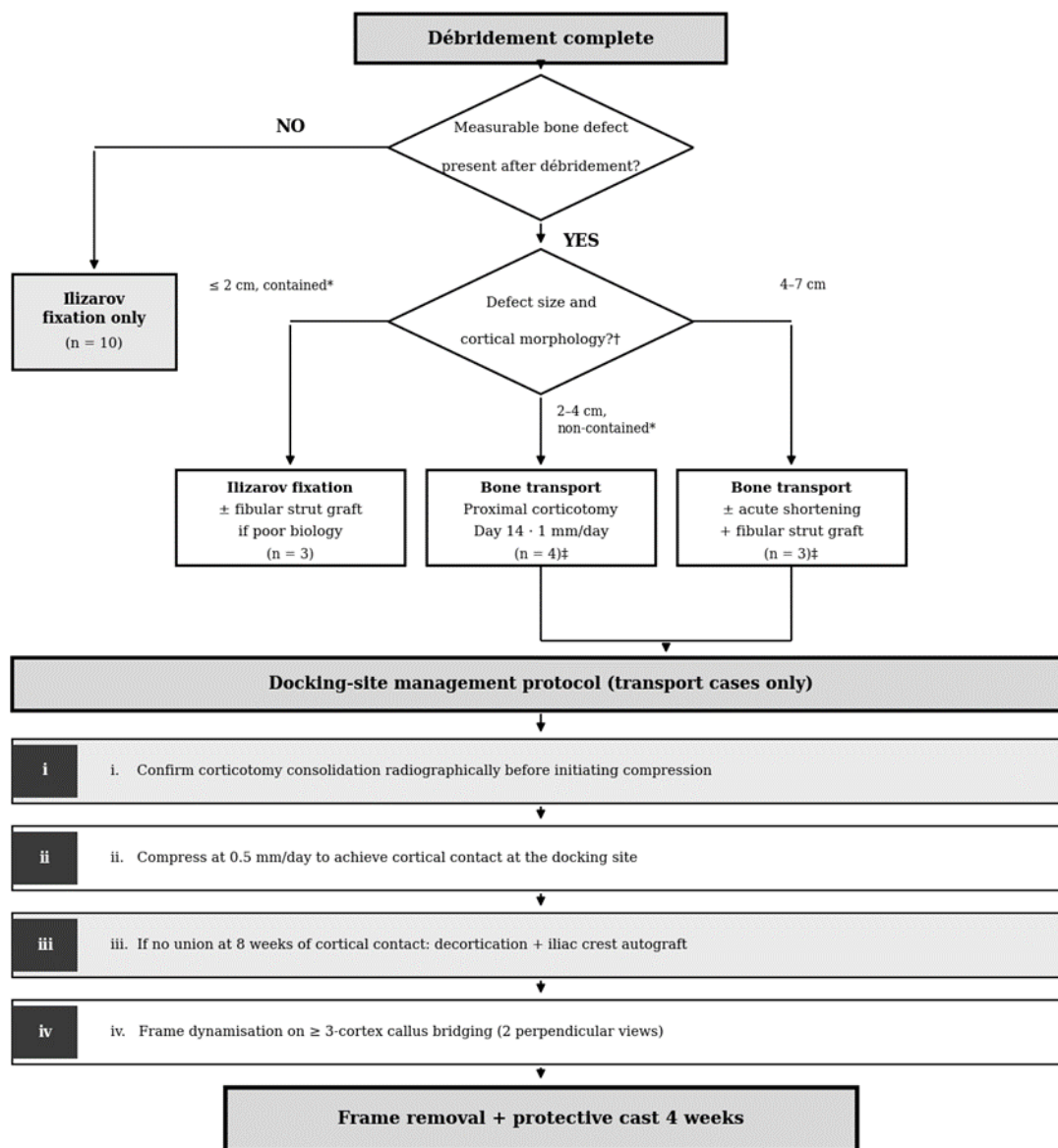
Life Support (ATLS) framework, with concurrent resuscitation, haemodynamic stabilisation, and empirical broad-spectrum intravenous antibiotics. Each patient underwent systematic clinical assessment documenting wound size, contamination, distal pulses, and neurological status. Plain anteroposterior and lateral radiographs were obtained for all limbs; computed tomography (CT) scanning was added selectively when intra-articular involvement was suspected. Gustilo-Anderson grading was assigned intraoperatively by the operating surgeon at the time of debridement.

Surgical technique

Surgery was performed under general or regional anaesthesia. Debridement began with systematic wound extension — entry and exit wounds were opened longitudinally to expose the full projectile track. Skin, subcutaneous tissue, fascia, and muscle were excised to healthy, bleeding margins. Irrigation used at least 9 L of normal saline; antiseptic additives were deliberately avoided²⁰. Free cortical fragments were removed; those retaining a periosteal sleeve were preserved. Every fracture was stabilised definitively with an Ilizarov circular external fixator during the same operative session, with frame architecture tailored to fracture level and pattern; three patients required supplementary lag screw fixation for intra-articular involvement.

Bone defect management followed a structured, size- and morphology-based algorithm (Figure 1). Where no measurable defect was present after debridement ($n=10$), Ilizarov fixation alone was applied. Contained defects of 2 cm or less with at least one intact cortex ($n=2$) were similarly managed without supplementary grafting, as preserved cortical continuity provided sufficient biological and mechanical stability for union. In one patient with a Gustilo IIIB diaphyseal fracture, extensive comminution with multiple devitalised cortical fragments created a severely compromised biological environment at the fracture site despite the absence of a discrete measurable segmental gap; primary fibular strut autografting was performed at the fracture site as biological augmentation, as documented intraoperatively.

Non-contained defects of 2–4 cm ($n=4$) were treated by bone transport via a proximal metaphyseal corticotomy, initiated on postoperative day 14 at 1 mm/day divided into four equal daily increments. Defects of 4–7 cm ($n=3$) were managed by bone transport; for the largest defect of 7 cm, acute shortening was performed in combination with bone transport to



* Contained defect: ≥ 1 intact cortex providing biological and mechanical continuity.

† Intraoperative assessment of cortical integrity, bone quality, and soft-tissue vascularity informs the decision at the 2-4 cm boundary; this zone of clinical judgement is acknowledged as a source of protocol variability.

‡ Bone transport n values: non-contained 2-4 cm (n = 4), 4-7 cm (n = 3). One additional patient received fibular strut grafting at the fracture site for severe comminution without a discrete segmental defect.

Fig. 1 — Bone defect management decision algorithm. The algorithm summarises the size- and morphology-based framework applied across all three participating centres. The boundary between contained ≤ 2 cm defects managed without transport and non-contained 2-4 cm defects treated by bone transport represents a zone of intraoperative clinical judgement, as discussed in the Methods section.

reduce the required transport distance, supplemented by fibular strut autografting at the docking site.

Docking-site management for all transport cases followed a four-step protocol: (i) confirming corticotomy consolidation radiographically before initiating compression; (ii) progressive compression

at 0.5 mm/day to achieve cortical contact; (iii) if union had not occurred within eight weeks of cortical contact, open decortication with iliac crest corticocancellous autografting was performed; and (iv) frame dynamisation was initiated upon bridging callus across at least three of four cortices

on two perpendicular views. The boundary between contained small defects and non-contained defects requiring transport represents a zone in which intraoperative assessment of cortical integrity, bone quality, and soft-tissue vascularity informed the final decision; this judgement is acknowledged as a source of protocol variability that future prospective studies should address with predefined intraoperative criteria.

Fourteen patients (70%) achieved primary wound closure without undue tension; the remaining six underwent staged closure or skin grafting at seven to ten days once infection had been excluded and healthy granulation tissue confirmed.

Postoperative care

Neurovascular observations were recorded six-hourly for the first 48 hours. Antibiotics continued for 48 hours postoperatively and were extended for patients awaiting delayed wound closure. All patients received low-molecular-weight heparin until they were independently mobile. Physiotherapy began on day one, prioritising active knee and ankle exercises; patients progressed to partial weight-bearing through the frame with axillary crutch support as comfort allowed.

Follow-up and outcome assessment

Review appointments were fortnightly for the first three months, then monthly until frame removal. Union was defined radiographically as bridging callus across at least three of four cortices on two perpendicular views, and clinically as pain-free full weight-bearing after frame dynamisation. After frame removal, all patients received a protective below-knee cast for four weeks. The primary endpoint was fracture union rate; secondary endpoints were fixation duration, total number of operations, and the full complication profile (pin-tract and deep infection, joint stiffness, angular deformity, and limb length discrepancy). Pin-tract infections were classified according to the Checketts-Otterburn grading system²².

Statistical analysis

All analyses were performed using IBM SPSS Statistics for Windows, Version 23.0 (IBM Corp., Armonk, NY, USA). Continuous data are presented as mean $\pm$ standard deviation (SD) with full range; categorical data as count and percentage. No formal a priori sample size calculation was performed, as this was a single-arm descriptive cohort study without a comparative intervention group; the 20 patients enrolled represent the total consecutive eligible

population at the three participating centres during the five-year study period.

RESULTS

Demographics and injury profile

All 20 patients were male, with a mean age of 29.7 ± 8.42 years (range 21–51); 60% were under 30 years of age. The right leg was injured in 12 patients (60%). Machine gun fire caused 18 injuries (90%); two resulted from shotgun pellets. Thirteen fractures (65%) occupied the tibial diaphysis, five (25%) the distal metaphysis, and two (10%) the proximal metaphysis; three patients (15%) had intra-articular extension. Gustilo-Anderson grading was weighted towards severe injury: 14 fractures (70%) were grade IIIA and six (30%) grade IIIB. After debridement, bone defects were documented in ten patients (50%), seven with gaps under 4 cm and three with gaps of 4–7 cm. The three patients with defects of 4–7 cm all underwent bone transport; acute shortening was additionally performed in the patient with the largest defect (7 cm) to reduce transport distance, supplemented by fibular strut autografting at the docking site. Six patients (30%) required skin grafting. Full demographic and injury data are presented in Table I.

Union and treatment duration

Nineteen of 20 patients (95%) achieved fracture union. The single case of non-union occurred in a type IIIB fracture in which a large residual gap persisted at the docking site following bone transport. Union was ultimately achieved after frame revision and supplementary autologous iliac crest grafting, approximately six months after frame revision. The frame remained in situ for a mean of 12.3 ± 7.28 months (range 7–36), with the wide variation reflecting differences in injury severity and the additional time demands of bone transport cases. All patients were followed for one year after frame removal, yielding a mean total clinical follow-up of approximately 24 months (range 19–48 months). Each patient underwent a mean of 2.45 ± 2.06 procedures (range 1–8). Union and treatment data are presented in Table II.

Complications

Pin-tract infection occurred in 17 patients (85%) and was the most commonly encountered complication. In every case this was superficial, classified as Checketts-Otterburn Grade 1 or 2, responding to intensified local pin-site hygiene and a short course of oral antibiotics; no patient required pin removal or

Table I. — Demographic data, fracture characteristics, Gustilo-Anderson grade, and bone defect status among the 20 study patients.

Variable		n (%) or mean $\pm$ SD
Age (years)	Mean $\pm$ SD	29.7 $\pm$ 8.42
	Range	21–51
Age group	21–30 years	12 (60%)
	31–40 years	5 (25%)
	> 40 years	3 (15%)
Sex	Male	20 (100%)
	Female	0 (0%)
Side injured	Right	12 (60%)
	Left	8 (40%)
Mechanism	Machine gun	18 (90%)
	Shotgun	2 (10%)
Fracture location	Diaphysis (shaft)	13 (65%)
	Distal metaphysis	5 (25%)
	Proximal metaphysis	2 (10%)
Intra-articular extension	Absent	17 (85%)
	Knee joint	1 (5%)
	Ankle joint	2 (10%)
Gustilo-Anderson grade	Type IIIA	14 (70%)
	Type IIIB	6 (30%)
Skin grafting required	No	14 (70%)
	Yes	6 (30%)
Bone defect	None	10 (50%)
	< 4 cm	7 (35%)
	$\geq$ 4 cm	3 (15%)
Bone transport performed	No	13 (65%)
	Yes	7 (35%)
Bone grafting performed	No	17 (85%)
	Yes (fibular autograft)	3 (15%)

Table II. — Fracture union, duration of external fixation, and number of surgical procedures.

Variable		n (%) or mean $\pm$ SD
Fracture union	Achieved	19 (95%)
	Docking-site non-union	1 (5%)
Duration of fixation (months)	Mean $\pm$ SD	12.3 $\pm$ 7.28
	Range	7–36
Surgical procedures per patient	Mean $\pm$ SD	2.45 $\pm$ 2.06
	Range	1–8

emergency frame revision. Deep surgical site infection occurred in one patient (5%), necessitating operative debridement and prolonged intravenous antibiotics. Ankle stiffness was predominantly a mild restriction of the terminal arc of dorsiflexion and plantarflexion, affecting seven patients (35%); one ultimately required arthrodesis. Knee stiffness occurred in two patients (10%). Axial malalignment (tibial varus in two patients, ankle equinus in one) was present in three patients (15%). Limb length discrepancy occurred in three patients (15%), all arising in patients who had undergone bone transport; those with functionally significant shortening were offered

staged lengthening. No neurovascular complication attributable to the injury or fixation technique was recorded throughout follow-up. Complication data are summarised in Table III.

Retrospective review of clinical records at final follow-up identified return-to-work and ambulatory status data for all 20 patients. Nineteen of 20 patients (95%) returned to work; 11 (55%) resumed the same occupation without limitations and 8 (40%) returned with occupational modifications. The single patient who had not returned to work at final follow-up was the non-union case, in whom the prolonged treatment course resulted in permanent occupational disability.

Table III. — Complications recorded during the study period.

Complication		n (%)
Knee stiffness	Absent	18 (90%)
	Present	2 (10%)
Ankle stiffness	Absent	13 (65%)
	Present	7 (35%)
Pin-tract infection	Absent	3 (15%)
	Superficial pin-tract infection (Checketts-Otterburn Grade 1–2; conservative management)	17 (85%)
	Deep pin-tract infection (Checketts-Otterburn Grade ≥ 3 ; operative management)	0 (0%)
Surgical site infection	Absent	19 (95%)
	Present (deep, operative management)	1 (5%)
Axial deformity	None	17 (85%)
	Varus malalignment	2 (10%)
	Equinus deformity (ankle)	1 (5%)
Limb length discrepancy	None	17 (85%)
	< 1 cm	1 (5%)
	4 cm	1 (5%)
	5 cm	1 (5%)

Seventeen patients (85%) walked without a limp at final follow-up; the remaining three had mild gait disturbance, of which two resolved following limb length discrepancy correction.

Case illustration

A 21-year-old male soldier presented with a high-velocity machine gun wound to the left leg. Examination revealed a Gustilo type IIIA injury: a 1

$\times$ 1 cm lateral entry wound and a 2 $\times$ 3 cm medial exit wound with intact distal neurovascular status (Fig. 2). Radiographs confirmed a comminuted distal tibial fracture without joint involvement. Following ATLS resuscitation and initiation of broad-spectrum intravenous antibiotics, the patient was taken to the operating theatre on the day of admission. The wound was extended, debrided systematically, and irrigated with 9 L of saline; primary closure was achieved and

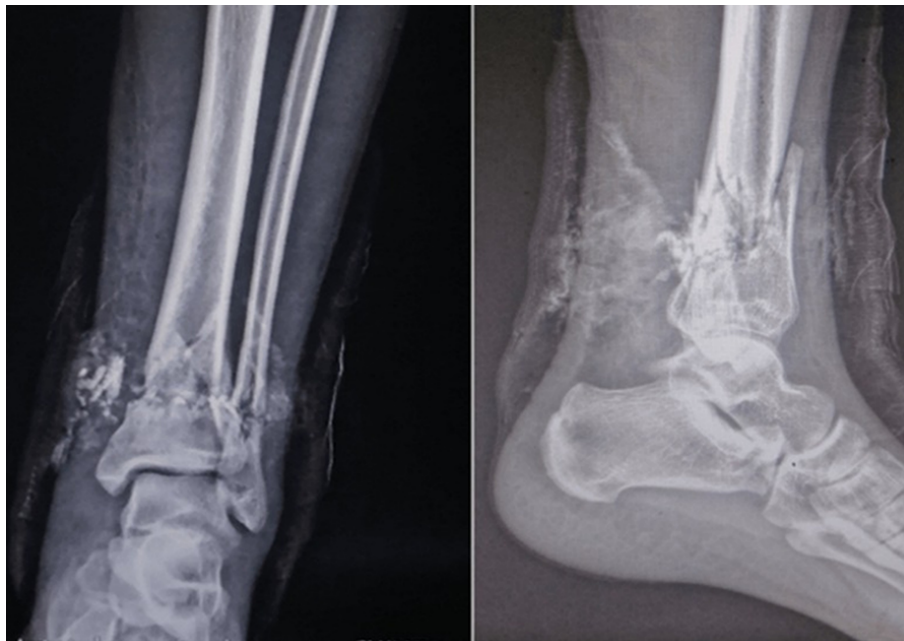


Fig. 2 — Initial anteroposterior and lateral radiographs of a 21-year-old male soldier with a Gustilo type IIIA open fracture of the distal left tibia from high-velocity machine gun injury. The lateral entry wound measured 1 $\times$ 1 cm and the medial exit wound 2 $\times$ 3 cm. Distal neurovascular status was intact on admission.

an Ilizarov circular fixator applied (Fig. 3). Superficial pin-tract infection at three months resolved with local wound care and oral antibiotics. Clinical and radiographic union criteria were met at seven months; the frame was removed and a below-knee cast applied for four weeks. At 12 months, radiographic examination showed complete cortical remodelling with no residual deformity (Fig. 4), and the patient returned to full unassisted weight-bearing with a full arc of knee and ankle motion and no limb length inequality.

DISCUSSION

Our series of 20 consecutive Gustilo type III gunshot tibial fractures managed with a structured Ilizarov protocol achieved a 95% union rate without amputation, adding to the growing evidence supporting circular external fixation as an effective treatment option for this injury type. The five-step protocol — comprising aggressive debridement, definitive Ilizarov stabilisation, staged wound closure, bone transport for segmental defects, and planned docking-site grafting — can be delivered at any centre with access to an Ilizarov set and a committed surgical team. No microsurgical infrastructure or expensive implants are required. These findings are descriptive and do not establish superiority over alternative fixation strategies, including intramedullary nailing in selected cases or hybrid external fixation.

The demographics of our series are consistent with the military and civilian epidemiology of gunshot

trauma described by others¹². Young men in their late twenties predominate, and the Gustilo distribution (70% IIIA, 30% IIIB) reflects the severity expected from high-velocity mechanisms. Bayrak et al., working with a mixed-mechanism gunshot series, reported a somewhat lower proportion of type III injuries and an older mean patient age¹³. The relative youth and injury severity of our cohort most likely reflect the military predominance of our source population.

Our 95% union rate sits at the optimistic end of published experience. Papaioannou et al. found non-union in approximately one in five patients managed with external fixation for open tibial fractures,¹⁴ whereas Wani et al. and Hosny and Fadel each achieved 100% union^{5,18}. Keeling et al., reporting short-term outcomes of severe open wartime tibial fractures managed with ring external fixation, similarly documented successful union in the majority of cases²¹.

The Ilizarov technique has been widely used for the management of large post-traumatic tibial bone defects, with bone transport providing a reliable method for limb reconstruction when conventional techniques are insufficient²³.

Our single non-union arose at the docking site of a type IIIB bone transport case — a recognised complication of distraction osteogenesis rather than a failure of the overall strategy — and ultimately resolved with additional surgery.

The mean fixation duration of 12.3 months reflects injury severity. Bone transport cases and delayed presentations extend the treatment timeline

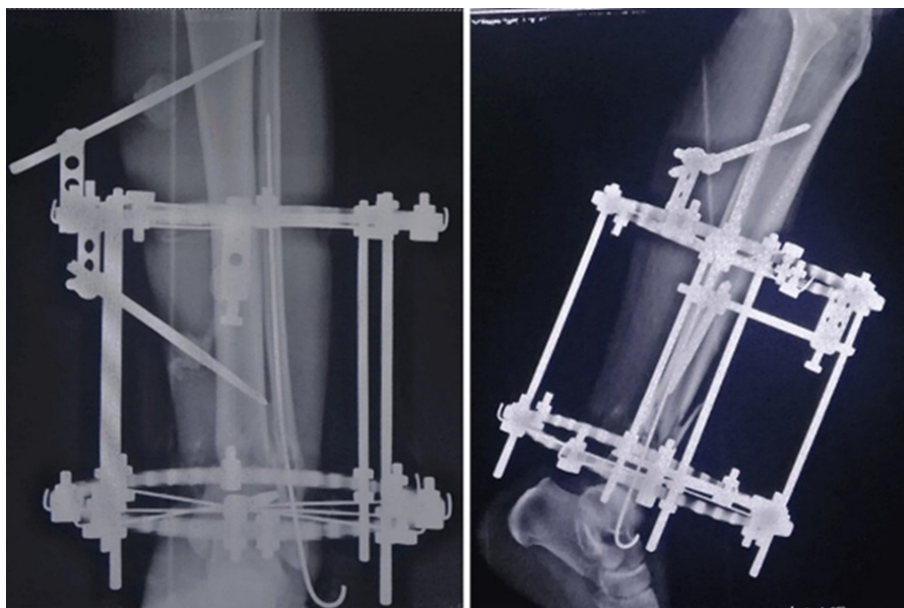


Fig. 3 — Intraoperative anteroposterior and lateral radiographs after wound debridement and primary closure, with the Ilizarov circular external fixator in place following definitive stabilisation performed on the day of admission.



Fig. 4 — Anteroposterior and lateral radiographs at 12-month follow-up confirming complete cortical remodelling. The frame was removed at seven months, followed by four weeks in a protective below-knee cast. The patient achieved a full arc of knee and ankle motion with no angular deformity at this point.

considerably. Realistic counselling from the outset regarding duration, pin-site care demands, and return-visit requirements is, in our experience, one of the most important determinants of compliance and ultimately of outcome.

The pin-tract infection rate of 85% is consistent with rates reported in the Ilizarov literature for comparable fixation durations and anatomical locations, which range from 30% to over 90% in series involving prolonged fixation in contaminated environments. Crucially, all infections in this series were superficial (Checketts-Otterburn Grade 1 or 2),²² responding to local wound care and short-course oral antibiotics without pin removal, frame revision, or operative debridement; none progressed to osteomyelitis. The clinically important distinction is between superficial pin-tract infections which are a predictable and manageable feature of prolonged fixation and deep infection that threatens the limb. Our deep infection rate of 5% compares favourably with unreamed nailing series in comparable injury grades¹⁶.

The versatility of the Ilizarov frame in simultaneously addressing bone loss and soft-tissue defects has been previously highlighted in complex tibial injuries^{23,24}. Recent work has also demonstrated that the Ilizarov frame can contribute to soft-tissue management, including progressive wound closure in complex lower limb injuries without the need for microsurgical reconstruction²⁵.

Ankle stiffness (35%) is the complication most amenable to prevention. The ankle is mechanically vulnerable during prolonged tibial fixation, particularly in distal injuries where patients adopt a protective equinus posture. We now regard physiotherapy beginning on day one and continuing throughout fixation as fundamental to treatment. Limb length discrepancy occurred exclusively in the bone transport subgroup; all patients with functionally significant shortening were offered secondary correction.

Recent reports combining Ilizarov techniques with staged reconstruction strategies further support

its role in limb salvage for complex infected tibial injuries with bone loss²⁶.

The principal strengths of this study are its prospective design, multicentre recruitment, and adherence to a predefined protocol with objective endpoints and transparent complication reporting. Limitations are as follows. First, the sample size is modest (n=20) and the absence of a comparative arm precludes any inference of superiority over alternative fixation strategies; these findings are descriptive. Second, validated patient-reported functional outcome measures (LEFS, AOFAS, SF-36) were not administered prospectively, and return-to-work and ambulatory status data were retrieved retrospectively from clinical records rather than through predefined prospective assessment; future studies should incorporate these instruments from enrolment. Third, mean total follow-up was approximately 24 months (range 19–48 months), meeting the two-year minimum recommended for surgical outcome studies; late complications including post-traumatic arthritis, refracture, and long-term functional deterioration cannot be reliably excluded. Fourth, the exclusively male, predominantly military cohort limits generalisability: extrapolation to female patients, civilian gunshot victims with different injury energetics or wound bacteriology, or non-military healthcare contexts should be made with caution and requires prospective validation. Future work, ideally multicentre and prospectively comparative, should address these gaps.

CONCLUSION

When applied within a structured protocol, Ilizarov circular external fixation handles the full spectrum of challenges posed by high-velocity gunshot tibial fractures — skeletal instability, contamination, soft-tissue loss, and segmental bone deficiency — within a single coherent treatment framework. Our results support the Ilizarov circular frame as a feasible and effective option for this injury type, particularly in resource-limited, high-volume trauma settings where the conditions required for safe internal fixation are rarely met. Whether it offers superior outcomes to alternative fixation strategies cannot be determined from this study design and warrants prospective comparative investigation. We therefore encourage future prospective, comparative studies that extend recruitment to female patients and civilian populations, to confirm the generalisability of these findings and to better define the role of the Ilizarov technique relative to alternative fixation strategies.

Ethics approval: Ain Shams University Faculty of Medicine Ethics Committee (reference: FWA 00017585).

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