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The tibial transverse technique: an advanced approach to limb salvage strategies for non-healing diabetic foot ulcers with peripheral vascular disease using Ilizarov principles

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Executive summary

Diabetic foot ulcers (DFUs) are a disabling and in most instances life-threatening diabetic complication, particularly when superimposed on peripheral vascular disease (PVD). DFUs are notoriously refractory to traditional treatments and therefore evolve into chronic non-healing ulcers, severe infections, and ultimately high rates of lower limb amputations. The strong clinical demand for effective limb salvage surgeries has prompted the pursuit of novel surgical strategies.[1–3] The Tibial Transverse Technique (TTT), a novel surgical procedure founded on the underlying principles of Ilizarov's distraction osteogenesis, offers an exciting opportunity for treatment of critical ischemia and healing in dysvascularized diabetic feet. This method capitalizes on the body's natural regenerative capacity through controlled mechanical stimulation. The power of TTT comes from its unique ability to induce neovascularization, significantly improve microcirculation, and stimulate far-reaching soft tissue regeneration by tension-stress stimulation.[4,5] Robust clinical evidence, both as large patient numbers and detailed case histories, always yield high wound healing rates, measurable improvement in vascular measures such as Ankle-Brachial Index (ABI) and Transcutaneous Oxygen Measurement (TcPO2), and dramatic limb salvage rates. These outcomes collectively avoid major amputations and halt gangrenous advancement.[6]

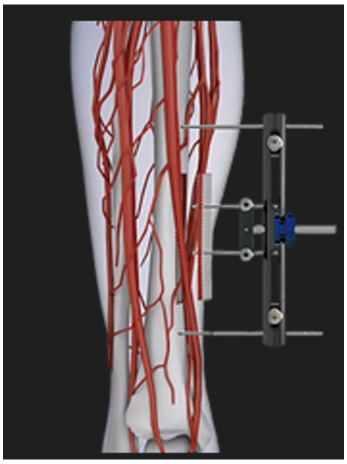

Figure 1 Tibial transverse technique using Ilizarov principles.

The successful application of TTT, even in critically comorbid individuals and those with a history of failed vascular interventions, renders it a revolutionary treatment. It represents an acceptable and often curative solution for those otherwise inevitable limb loss, thus redefining the treatment algorithm for refractory.[7]

Introduction: the clinical challenge of diabetic foot ulcers and peripheral vascular disease

Prevalence and Burden of DFUs and PVD

About 15% of diabetics will have developed a diabetic foot ulcer at some point in their lives; it is a major common, and serious complication. Diabetic ulcers are largely what motivate the most significant medical issue in the diabetic patient presenting to the medical clinic and is the reason for most amputations to the lower extremities (nearly 85% of all nontraumatic amputations). The risk of foot ulceration and limb amputation will be significantly probable, especially with age and chronicity of diabetes. The incidence of lower limb amputations from diabetic foot ulcers suggests a reasonable burden to public health, It also implies that diabetic patients' quality of life, and limb salvage will be best predicted by successful DFU management compared to wound closure. The statistics on amputation would point towards the potential for a strong intervention to minimize these debilitating consequences, revealing a systemic deficiency in the majority of patients, in current treatment options.[8]

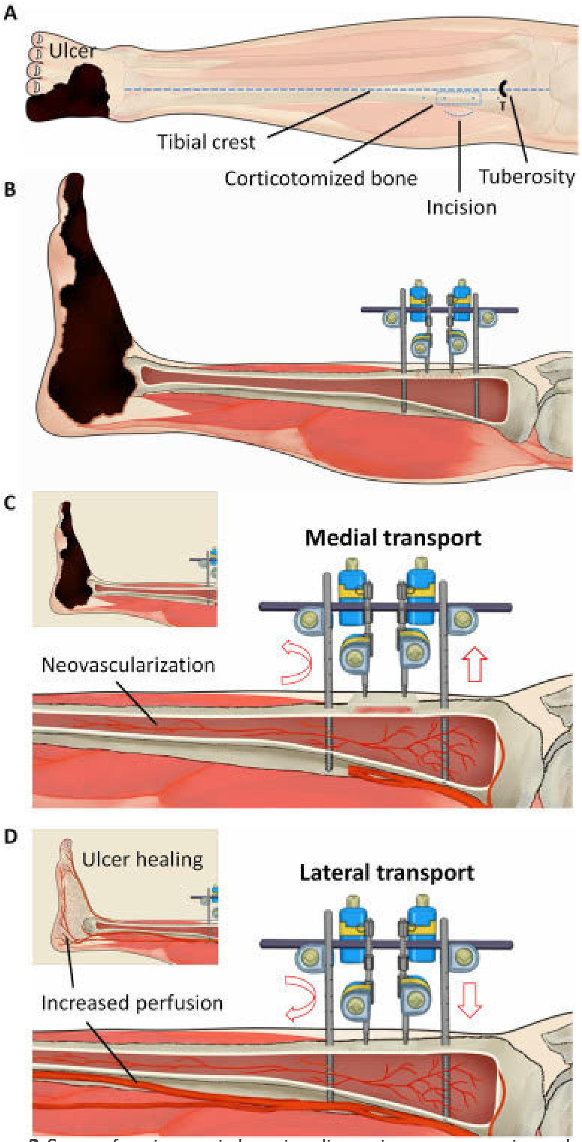

Figure 2 Steps of angiogenesis by using distraction osteogenesis method of Ilizarov principles.

Pathophysiology of non-healing DFUs in the context of PVD

Its chronic nature as non-healing wounds is a result of multi-factorial, complex pathophysiology with a highly complex interaction between peripheral neuropathy, peripheral arterial disease (PAD) or vascular insufficiency, chronic inflammation and impaired tissue regeneration.

Peripheral neuropathy: A major causative factor in almost 90% of DFUs. Continued exposure to high glucose levels causes injury to sensory, motor and autonomic nerves. Sensory nerve damage results in loss of protective sensation, and thus the patients won't enjoy pain, temperatures, or minor injury or trauma that would otherwise go on to ulcer without the patient noticing. Motor neuropathy results in weakness of muscles in the foot deformities of foot architecture resulting in areas of focally increased pressure and susceptibility to ulceration. Autonomic neuropathy interferes with sweat secretion and leads to dry, fissured, and cracked skin, which is prone to trauma and risk of infection.

Peripheral Arterial Disease (PAD) / Ischemia: Diabetic patients tend to develop vascular disease, namely in the peripheral arteries of the lower limbs. PAD is characterized by obstruction or narrowing of the vessels due to atherosclerosis, significantly impairing blood supply to the extremities. This compromised circulation minimizes significantly the transport of essential oxygen, nutrients, and infection-clearing immune cells to areas surrounding wounds, while simultaneously inhibiting the elimination of waste products. Consequently, healing of wounds is halted in a perpetual state of inflammation, leading to tissue hypoxia, compromised regeneration, and ultimately tissue death and gangrene, with some cases necessitating amputation.[2,8]

Impaired wound healing & chronic inflammation: Direct causation of the pathogenesis of non-healing wounds by sustained hyperglycemia. It creates oxidative stress, endothelial dysfunction, and a chronic state of inflammation which actively delays healing. Hyperglycemia also initiates metabolic reprogramming of immune cells to generate sustained inflammation, impaired macrophage plasticity, and resistance to normal tissue remodeling. Advanced Glycation End-products (AGEs) formation is increased in diabetes; AGEs accumulate on matrix proteins, making the tissues stiff and disrupting cellular communication needed for repair. After binding to their receptor (RAGE), AGEs trigger inflammatory cascades that increase endothelial dysfunction and reactive oxygen species generation, also causing cell injury and wound healing impairment. The normal linear progression of the processes of wound healing (hemostasis, inflammation, proliferation, and remodeling) is broken in chronically non-healing DFUs, which preferentially become bogged down in one or more of these processes.[2,3,10]

Infection: Diabetic foot ulcers are direct entry points to systemic infections like cellulitis and osteomyelitis (infection of the bone). These infections are especially risky in diabetic patients due to their compromised immune mechanisms. Infection also impairs healing of the wound, aggravates damage to the tissue, and may rapidly progress to gangrene, which usually necessitates total amputation. The overlap of neuropathy, ischemia, and chronic inflammation produces a cycle that effectively bars healing of the wound. This complicated, multi-etiology pathology accounts for why single therapeutic interventions, such as solitary wound care or revascularization therapy, commonly fail to bring about durable improvement[2].

Neuropathy damages in ignorance, ischemia inhibits healing, and inflammation due to hyperglycemia actively interferes with the body's repair mechanisms even in the presence of some blood supply. This triple threat is the explanation for the recalcitrant character of the ulcers and the frequency of amputations (Table 1).

Limitations of conventional treatments and the imperative for limb salvage strategies

Traditional treatment of DFUs typically encompasses strict glycemic control, meticulous local wound care (e.g., debridement and off-loading), and, where feasible, revascularization procedures to restore blood supply. However, for a significant percentage of patients, particularly those with CLI where ulcers do not heal even after the above traditional treatments or where vascular intervention has failed, advanced surgical interventions are urgently needed. The widely documented drawbacks of conventional therapies, including a high recurrence rate and the phenomenon of revascularization procedures being insufficient or failing, exemplify a critical unmet clinical requirement. DFU recurrence after initial healing with medical and surgical debridement as low as 40% within one year is mainly due to persisting underlying ischemia and hypoxia. Here,

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TTT does not only look like a last-resort therapy but also like a life-sustaining limb salvage procedure, particularly for those patients with limb-threatening amputation after other avenues have been pursued. This highlights the requirement for intervention capable of altering radically the local tissue milieu and the microcirculation beyond temporary wound closure or superficial revascularization.[1,11]

Table 1 Pathophysiology of non-healing diabetic foot ulcers in PVD

Factor	Mechanism	Impact on wound healing
Peripheral Neuropathy	Loss of protective sensation; Motor/autonomic dysfunction; Impaired sweat production	Unnoticed trauma, foot deformities; Skin cracking/fissuring; Increased pressure points; Predisposition to ulceration and infection
Peripheral Arterial Disease (PVD)/ Ischemia	Reduced blood flow due to arterial narrowing/ blockage (atherosclerosis); Impaired oxygen, nutrient, and immune cell delivery; Inefficient waste removal	Stalled healing; Tissue hypoxia; Necrosis; Gangrene; Increased infection risk; Amputation
Chronic Hyperglycemia/ Inflammation	Oxidative stress; Endothelial dysfunction; Advanced Glycation End-products (AGEs) formation and RAGE activation; Cytokine dysregulation; Impaired angiogenesis	Prolonged inflammation; Impaired tissue regeneration and remodeling; Increased tissue stiffness; Delayed healing; Cellular damage
Infection	Ulcer acts as portal for systemic infection (cellulitis, osteomyelitis); Impaired immune response in diabetes	Exacerbated tissue damage; Systemic complications; Delayed healing; Progression to gangrene; Amputation

Foundational principles: the Ilizarov method and distraction osteogenesis

Overview of Ilizarov's tension-stress effect and its application in tissue regeneration

The Ilizarov method, also known by the official name transosseous compression-distraction osteosynthesis, was a revolutionary advancement in distraction osteogenesis and lengthening and reconstruction of the bone. Invented by Prof. G.A. Ilizarov, a series of extensive experimental studies conducted under his leadership set down optimal conditions for the successful use of distraction osteogenesis. These are stable fixation of the bone fragments with an external equipment, minimally invasive corticotomy, and controlled, smooth rate of distraction, typically 0.75-1 mm per day, divided into three or four increments[2].

The foundation of the Ilizarov method is the "tension-stress effect," a finding recognized in the USSR in 1989. Based on this effect, the application of progressive, persistent tension to living tissues evokes their active regeneration and growth. This biological effect was investigated strictly with the assistance of meticulous radiographic, histological, and biochemical analysis. The profound implications of this method reside in its potential to biologically engineer new tissue in vivo, rather than relying on transplantation or grafting techniques. This is a paradigm shift from static repair strategies to dynamic induced tissue regeneration, at the core of what TTT's therapeutic potential is all about.[2,5,11]

Mechanisms of bone and soft tissue growth induced by gradual distraction

Distraction osteogenesis has been directly demonstrated to form new bone mass and restore skeletal continuity by filling segmental gaps. Its regenerative potential because of slow distraction, however, extends much beyond bone tissue. In Prof. Ilizarov's studies, the other soft tissues in the limb, including muscles, nerves, ligaments, tendons, and skin, were also observed to react actively to slow distraction. This promotes tension evokes or enables their evocation, enhances their biosynthetic activity, and hastens energy exchange between such tissues.[7]

Therapy usually commences with a primary low-energy osteotomy or corticotomy, performed at a site distal to the pathologic area. An external fixator is then employed to gradually transfer a piece of bone under tightly controlled mechanical conditions. The most important theoretical step enabling one to use Ilizarov principles in the management of DFU is to generalize the tension-stress effect from bone tissue to all of the surrounding soft tissues, but particularly to the vascular system. That means systemic rather than local regeneration. The observation that soft tissues, i.e., blood vessels, respond to such controlled mechanical stress underlies the scientific basis for adapting the Ilizarov technique to counteract the primary deficit in PVD-DFUs: decreased vascularity and impaired healing of soft tissues. This extends the external validity of Ilizarov's original observation to severe ischemia, beyond its original orthopedic reconstruction.[6,8]

Tibial Transverse Technique (TTT): a novel approach for ischemic diabetic feet

Definition and evolution of ttt as a variation of Ilizarov principles

Tibial Transverse Technique (TTT) is a new and shortly-to-be-embraced method in branch salvage with an emotional success rate in diabetic ischemic ulcer healing. TTT is a variant or extension of the Ilizarov classical technique. Compared with transverse bone transport to bone deformity completion, TTT is transverse traction of an osteotomy tibial member.

One of the dynamic qualities of TTT is its intrinsic reparative bias when in classical distraction osteogenesis in new material creation new bone formation is the underlying issue, vascular kerchief revivification in the target original area is the underlying issue in TTT. It's an applied understanding of an age-conceived biomechanical principle to a particular pathological insufficiency-ischemia of DFUs. This shifting of the high function to vascular reconstruction of the kerchief is a giant vault too, since it allegedly heals the origin of the injured blood flux in PVD diabetic bases. Corticotomy area of pull was used in first TTT treatments, i.e., 5.0 cm x 1.5 cm. But changed modes subsequently improved this type further by segmenting the osteotomy into lower thickish bone windows, i.e., two 1.5 cm x 1.5 cm windows. It was achieved to reduce surgical trauma and risk of complications at the expense of minimal or zero loss in the most useful angiogenic creation effect. This evaluation features ongoing exposition of the fashion to minimal remedial benefit with less invasiveness, a primary concern in a patient population too often disabled by comorbidities.[7,8,11]

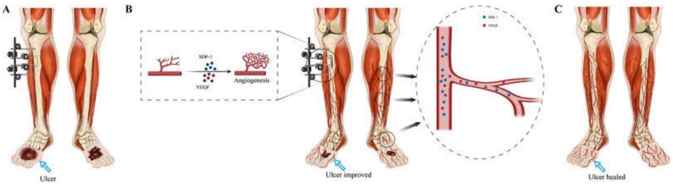

Figure 3 Process of diabetic foot ulcer healing by using Ilizarov principles distraction osteogenesis.

Detailed procedural steps: osteotomy, external fixation, distraction protocols

The treatment with TTT demands careful surgical procedure and distraction regimen after operation under strict control

Incision and osteotomy: The surgery is typically initiated with a long longitudinal incision cut on the medial aspect of the proximal or distal tibia. The subcutaneous tissue is lifted carefully, with the periosteum typically preserved intact. A unicortical osteotomy is then created. The extent of this osteotomy will be determined by the specific technique employed; for instance, one case series describes a 50x15mm unicortical osteotomy, while a group with 98 patients utilized two smaller 1.5cm x 1.5cm rectangular bone windows. The osteotomy is performed by drilling into the bone borders and completing the cut using an osteotome, usually converging into cancellous bone.

External fixation device: The limb is externally fixed after the osteotomy using an external fixator. Typically, it is the insertion of convergent Shanz pins into the unicortical transport segment, divergent pins being used to secure the

uniplanar external fixator (e.g., Orthofix). In modified techniques, the mobile external fixator pins are tightened into the bone windows and engage only the unilateral cortical bone for the transport of the bone block, and the remaining external fixator needles transfix both cortices of the bone to provide fixation to the entire construct. The rigorous control of distraction rate and rhythm, in addition to constant fixation, directly relates to the Ilizarov principle that the

"tension-stress effect" is very sensitive to ideal biomechanical conditions.[1,8]

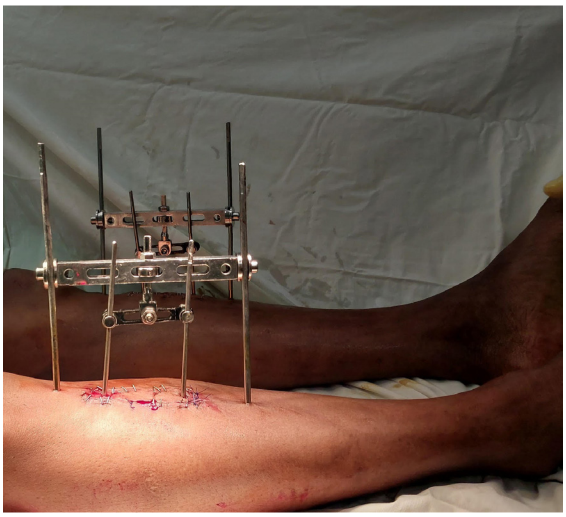

Figure 4 Tibial transverse technique applying in bilateral PVD

Distraction protocols: The other important component of TTT is the distraction phase under strict control:

Latency period: A latency period, typically between 5 to 10 days, is observed immediately after surgery prior to the start of distraction. This allows for primary healing and stabilization.

Rate of distraction and rhythm: Distraction begins progressively, at a rate of 0.5 mm per day or 1 mm per day, carefully divided into several increments over the course of a day. For example, 0.5 mm/day can be achieved through two 0.25 mm manipulations, or 1 mm/day through four different sessions.

Distraction time: The distraction persists for a defined time, e.g., 10 days to gain 7.5 mm of distraction, or two weeks in other regimens.

Redocking/compression: Following the distraction period, the transported bone segment can be compressed or "redocked" into its initial or alternate position, frequently over a comparable period to the distraction period.

Fixator retention: The external fixator is retained for an additional period of time, typically 6 to 8 weeks, or until radiographic confirmation of osteotomy healing is evident.[2]

Weight bearing: Weight-bearing patients are normally permitted throughout the treatment process, but off-loading of the involved heel when the ulcer just so happens to be present is provided with special directions.

Adjunctive procedures: TTT is typically included as part of a multi-modal treatment regimen. This typically consists of careful debridement of the wound, bone biopsies to ascertain the presence of osteomyelitis, preparation of the wound bed (for example, using a bovine skin substitute), wound vacuum therapy, and appropriate antibiotic therapy according to cultures. The reduction of osteotomy size in more recent procedures reflects a sustained refinement aimed at ensuring optimal therapeutic effect of angiogenesis while simultaneously reducing invasiveness and potential complications, and this is particularly important for diabetic patients whose tissues are potentially more fragile.[1,8,9]

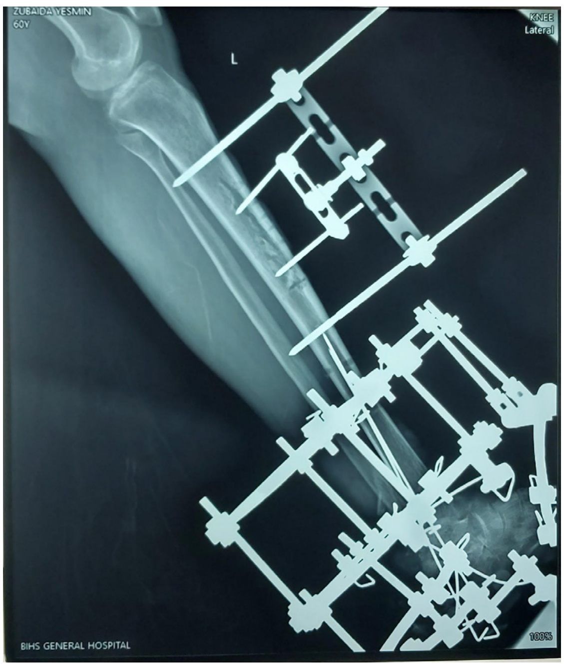

Figure 5 X-ray shows application of TTT device after corticotomy.

Mechanisms of angiogenesis and neovascularization induced by TTT

The therapeutic efficacy of TTT in ischemic diabetic foot is finally explained by its ability to aid the local regeneration of vessels and tissue through the gradual, slow creation of tension by the external fixator, using the tension-stress effect. The mechanism is multifaceted and involves a range of interdependent biological responses:

Cellular metabolism and microcirculation reconstruction: The constant, controlled distraction of the tibial cortex stimulates cellular metabolism and promotes tissue regeneration. The mechanical stimulus directly results in reconstruction of microcirculation in the affected limb by restoring and enhancing blood and oxygen supply to the lower limb. This improvement of lower limb microcirculation is one of the most important elements in facilitating the healing of chronic wounds.[2]

Growth factor release and angiogenesis: Mechanical stimuli generated through the gradual distraction of bone and surrounding soft tissues result in the release of a variety of growth factors, which have a role in angiogenesis. Studies have shown increased expression levels of key pro-angiogenic factors such as Vascular Endothelial Growth Factor (VEGF), basic Fibroblast Growth Factor (bFGF), Epidermal Growth Factor (EGF), and Platelet-Derived Growth Factor (PDGF). These factors play a role in the formation of new blood vessels.[10]

Oxygen demand and VEGF production: Microenvironmental changes resulting as a result of a distraction process alter local oxygen and nutrient demand at the site of stress. The above increased demand for oxygen, particularly in areas of tissue hypoxia, serves as an effective stimulus for the production of VEGF, a master gene regulator of angiogenesis.[6]

Osteoblastic activity and pro-angiogenic factor recruitment: The osteoblastic activity that is responsible for bone formation in distraction also triggers a cellular response that introduces additional pro-angiogenic factors that stimulate neovascularization.

Matrix remodeling: The extracellular matrix undergoes widespread remodeling during distraction. This remodels the matrix to create a facilitatory scaffold which permits new blood vessel ingrowth, thus creating the structural matrix of the newly formed microvasculature.

Distal blood flow enhancement: The increase flow is not a localized phenomenon at the osteotomy site. Distraction osteogenesis is accompanied by widespread angiogenesis and neovascularization of the soft tissues.

Besides, longitudinal distraction of the proximal tibia has been shown to induce increased and prolonged blood flow to the distal tibia. Such improvement in distal perfusion is particularly valuable in treating diabetic foot ulcers because it acutely addresses the metabolic requirements for the healing of distal soft tissue deficiencies.

Anti-inflammatory and neurological effects: Apart from its direct vascular benefits, TTT has been shown to also have an anti-inflammatory action and be able to assist patients' neurological function improvement. These additional benefits further optimally improve the local tissue environment, synergistically for better wound healing.[3]

The multi-mechanism of TTT, such as mechanical stimulation, growth factor induction, microcirculatory reconstruction, and even anti-inflammatory and neurological action, is an overall-spectrum biological response to ischemia of prolonged duration. Such a strategy goes beyond simple revascularization in that it actively constructs new, functional microvasculature and maximizes the local tissue environment for healing, an optimal strategy in the context of the complex, diffuse microvascular disease so frequently seen in diabetic foot disease. This active creation of new vascularity, rather than bypassing or dilating existing but diseased vessels, confers a definite therapeutic benefit in addressing the generalized microvascular dysfunction of diabetes.

Figure 5A

Figure 5B

Figure 5C

Figure 5D

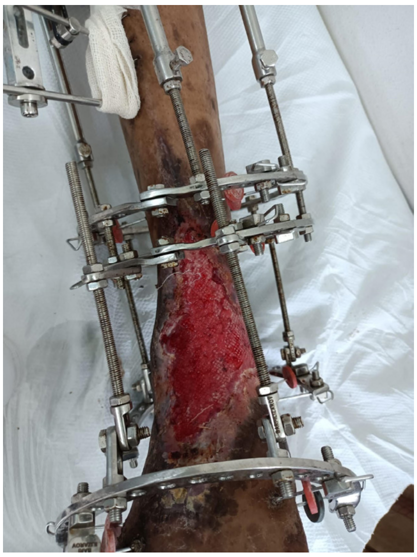

Figure 5E

Figure 5A,B,C,D,E Gradual healing of non healing diabetic foot ulcer after distraction osteogenesis by TTT device on Ilizarov principle.

Clinical effectiveness and outcomes of tibial transverse technique

Clinical use of the Tibial Transverse Technique proved to be highly effective in the management of the diabetic foot ulcer disorders complicated with peripheral vascular disease, particularly in wound healing, vascular enhancement, and limb preservation.

Figure 6A

Figure 6B

Figure 6C

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Figure 6D

Fig : 6E

Fig 6F

Fig 6G

Fig 6H

Fig: 6 I

Figure 6A,B,C,D,E,F,G,H,I Patient came with DFU over the both malleolus with uncontrollable DM . Gradual healing of the ulcer by Distraction Osteogenesis method of Ilizarov by TTT device

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followed by Split thickness skin graft.

Wound healing: rate, timeline, and ulcer conversions

TTT has been established to perform an important role in the prognosis of dysvascularized feet, particularly in patients with critical limb ischemia as well as those at risk for amputation. TTT's ability to convert chronic, non-healing ulcers into healing ulcers provides the basis for its therapeutic application.

Retrospective assessment of 98 diabetic foot patients presenting with Wagner grade ≥ 2 ulcers demonstrated 95.83% (92 out of 96 cases) successful wound healing after only postoperative care. The mean duration for wound healing was 53.18 ± 20.18 days in the group with individual variation from 21 to 108 days. Similarly in accordance with these findings, in a meta-analysis comprising 7 trials involving 818 patients, the rate of wound healing was 0.96 (95% CI: 0.93~0.98) after the end of TTT. Single-case series are also evidential of this effectiveness; in one of them, healing of non-healing heel ulcer at 20 weeks of starting of the TTT was observed. Another case documented healing of ulcer after 4 months of treatment. The uniformly high healing rates in refractory DFUs, and particularly unsuccessful standard treatment DFUs, would suggest that TTT is able to penetrate primary healing obstacles unavailable to other techniques and therefore must produce incredibly dramatic influences on pathophysiologic substrates to facilitate closure in resistant clinical situations.

Vascular improvement: objective measures and subjective improvements

One of the strongest pieces of evidence for the effectiveness of TTT is evidenced in its reported ability to improve peripheral circulation as validated by objective physiologic testing and subjective patient complaints.

Objective improvement of the vasculature after TTT. There was improvement seen in 98 patients with marked rehabilitation of Ankle-Brachial Index (ABI), a valuable marker of arterial lower limb perfusion, from preoperative mean of 0.55 ± 0.03 to 0.66 ± 0.06 at 3 months after the operation ($P<0.05$). WIFI grading, an internationally recognized limb risk stratification system, also showed significant improvement. Transcutaneous Oxygen Measurement ($TcPO_2$) and limb skin temperature, objective markers of microcirculatory potential, also significantly improved after the operation. Confirmation by sight of increased distal tibial perfusion has been demonstrated by a study of pre- and post-transverse tibial bone transport angiograms.

Reduction of subjective complaints also bears testimony to these objective improvements. Visual Analogue Scale of pain also reduced significantly, from 5.72 ± 1.17 pre-operative to 0.79± 0.99 at 3 months ($P<0.05$). Pain relief is because of the increased perfusion to the formerly ischemic tissue. Reduced. Objective decrease in ABI, $TCPO_2$, and WIFi classification and subjective decrease in pain firmly established the action of TTT on peripheral circulation augmentation. It is not merely a local wound response to the wound but also systemic augmentation of limb perfusion, and best for limb salvage in the long term and quality of life enhancement in PVD patients.

Amputation prevention and limb salvage

The objective of treatment of diabetic foot disease is prevention of major amputation and TTT has been an effective limb salvage modality. 7 studies with meta-analysis presented a very high overall pooled limb salvage rate of 0.98 (95% CI: 0.95~1.00) after TTT. Compared with control groups who did not receive any TTT, the intervention was significantly associated with better limb salvage rate (Odds Ratio: 9.65; 95% CI: 3.30~28.20; $p<0.001$). This kind of success has tough clinical evidence to support it; a case report even referenced that TTT was able to prevent an amputation below the knee in a patient with an ischemic foot and prior failed vascular interventions. Good limb salvage rates, ranging from 100% in a study and 98% in meta-analysis, are the most assured outcome with the most assured evidence of indication of limb salvage and prevention of amputation. Outcome is what makes TTT an excellent treatment with an excellent rate of prevention of DFUs' most severe complication.

Prevention of gangrene

Gangrene, a high-level necrosis of tissue as a consequence of severe ischemia and typically infection, is a simple pathway to extensive amputation in diabetic foot disease. Through substantial improvement in perfusion, TTT has a direct impact on prevention or development of gangrene.[10]

Of 98 operated patients screened, there were 52 patients with greater than one gangrenous toe. Despite this high presenting incidence, the healing of wounds after operation in the group was 95.83%. This may be in the form of salvage having been achieved on still viable gangrenous tissue, or even halt of progression, with subsequent loss of limb prevented. Peripheral neuropathy and inadequate perfusion are frequent etiologies of wound infection and subsequent gangrene, with amputation usually required. Through active restoration and stimulation of perfusion to the limb, TTT prevents such risks altogether, thereby preserving the limb from gangrene and its development or complication (Table 2).

Table 2 Key clinical outcomes of Tibial Transverse Technique for DFUs

Outcome category	Specific metric	Data source/study	Values
Wound Healing	Postoperative Healing Rate	Liu et al. (98 patients)	95.83% (92/96 patients)
	Pooled Healing Rate	Meta-analysis (7 studies, 818 participants)	0.96 (95% CI: 0.93~0.98)
	Average Healing Time	Liu et al. (98 patients)	53.18 ± 20.18 days (Range: 21-108 days)
	Time to Complete Healing (Case)	Case Report	20 weeks
Vascular Improvement	ABI Improvement (Pre- vs. Post-op)	Liu et al. (98 patients)	Pre: 0.55 ± 0.03; Post (3 months): 0.66 ±0.06 ($P<0.05$)
	WIFi Classification Improvement	Liu et al. (98 patients)	Significant improvement ($P<0.05$)
	VAS Pain Score Improvement (Pre-vs. Post-op)	Liu et al. (98 patients)	Pre: 5.72 ± 1.17; Post (3 months): 0.79 ±0.99 ($P<0.05$)

	Skin Temperature, TcPO2 Improvement	Meta-analysis	Significant improvement (P<0.05)
Limb Salvage	Pooled Limb Salvage Rate	Meta-analysis (7 studies, 818 participants)	0.98 (95% CI:0.95~1.00)
	Amputation Avoidance (Case)	Case Report	Successful avoidance of below-knee amputation
Complications	Overall Complication Rate	Liu et al. (98 patients)	6.12% (6 patients)
	Pin Tract Infections	Liu et al. (98 patients)	3 patients (managed)
	Amputation Post-TTT	Liu et al. (98 patients)	3 patients (due to uncontrolled infection ,any other medical causes,Co- morbidities)
	Mortality	Liu et al. (98 patients)	0% patient
	Ulcer Recurrence	Liu et al. (98 patients)	0% (during follow-up)

Illustrative clinical cases

The success of the Tibial Transverse Technique is further described with the help of clinical case reports, which establish its application and outcome in difficult patient cases.

Case 1: Refractory heel ulcer with failed vascular intervention

This was a 64-year-old female with extensive medical history, including insulin-dependent diabetes of long standing, peripheral neuropathy, end-stage renal disease on hemodialysis, and peripheral vascular disease status post-failed balloon angioplasty. Most prominent of all, however, was her PVD status post-failed balloon angioplasty, which pointed to the refractoriness of the disease to conventional revascularization.

The patient presented with a chronic non-healing ulcer on her left heel for over one year, which started as an abrasion. The clinical presentation of note was the lack of palpable dorsalis pedis and posterior tibial pulses, a sign of extensive arterial insufficiency, and loss of protective sensation. MRI also confirmed osteomyelitis of the calcaneus in the region surrounding the ulcer. Despite two previous peripheral angiograms and unsuccessful attempts at revascularization, the wound remained unclosed despite distal disease below the knee with peroneal and posterior tibial artery occlusion. Previous treatments, including debridement, biopsy-driven antibiotics, bovine skin substitute application, and wound vacuum therapy, also failed to close the wound. Because numerous conventional approaches failed and because the patient had numerous comorbidities, Transverse Tibia Transport (TTT) was performed.

The procedure involved a longitudinal skin incision over the medial proximal tibia and creation of a 50x15mm unicortical osteotomy. An external fixator with Shanz pins was applied. Distraction was initiated after 10 days of latency at 0.5 mm/day (two increments of 0.25 mm) for 20 days to achieve 10 mm of distraction.The fixator was maintained for an additional 6 weeks and was removed at 3 months postop, when healing of the osteotomy was confirmed radiographically. The patient was maintained on loading during treatment with heel off-loading training. The clinical outcome was excellent.

Wound closure was achieved at 20 weeks from the initiation of TTT. At one-year follow-up, the left heel ulcer was still closed and was complication-free, including pin site infections. One-year x-rays also demonstrated healing at the previous fixator sites. Perhaps more importantly, TTT successfully avoided a below-the-knee amputation, a significant success given the patient's prior failed vascular intervention and severe comorbidities. Comparative angiograms also demonstrated improved distal tibial perfusion post-procedure. This case amply demonstrates the usefulness of TTT as a limb salvage technique when other vascular interventions have failed. The patient's extreme comorbidities of end-stage renal disease, continued smoking, and chronic diabetes with osteomyelitis portray the particularly difficult nature of such a case and highlight the outstanding success of TTT in such a complex scenario.

Case 2: diabetic foot ulcer with prior amputations

He was a 45-year-old man with more than 20 years of Type 2 diabetes and corresponding Type 2 diabetic eye and nerve disease. His history was significant for past limb loss, two years previously having his right middle toe amputated for foot ulcers. His second left toe was amputated recently, just twenty days prior to his admission for the above therapy, due to an ulcer. Treatment in this patient involved total debridement of the extensive wounds, transverse tibial transport. Wound healing was uneventful after surgery.

The most important section of the report was the revascularization of the diseased limb in diabetic foot ulcer management. The report highlighted that tibial transverse transport prefers anastomotic branch reconstruction distal to the knee joint and induced membrane technology, when combined, further increases the local blood supply. This healing outcome in this instance, particularly in a patient with a past history of recurrent ulceration and several prior amputations, demonstrates TTT's key role in the prevention of further limb loss in highly compromised limbs. Combination therapy with antibiotic bone cement also demonstrates the application of TTT within the context of an intra-modal therapeutic strategy to complex DFU cases with an infectious component. This combination was touted as a cost-effective and efficient way of treating diabetic foot, an area given the reality that infection of diabetic foot is a leading cause of non-traumatic amputation

Complications and considerations

While the Tibial Transverse Technique has a number of advantages for refractory diabetic foot ulcers, complete comprehension of its application entails consideration of potential complications as well as adequate patient selection criteria.

Potential complications

While the overall outcome of TTT is superb, TTT is not without complications, though complication rates, as presented, appear to be low, especially in view of the severe comorbidities and high levels of disease of the patients undergoing this modality. In a series of 98 patients, the incidence of total complications was 6.12%.

Pin tract infections: Common complication of external fixation devices, pin tract infections occurred in three patients (of 98) in the aforementioned study. The infections were successfully treated with local disinfection and alcohol irrigation of the pin tract, and no one ended up with osteomyelitis. While pin channel infection is a recognized warning in meta-analyses, the successful outcome in this group shows that proper pin site care can avoid this complication.[4]

Amputation post-TTT: One should note that TTT, although very effective, is no panacea. Three (of 98) patients in the series went on to require amputation following TTT for refractory infection of the ulcer. Yet their amputated wounds did go on to heal, demonstrating that TTT does not always prevent amputation if severe, uncontrolled infection is not well controlled, further testifying to the importance of holistic DFU management including aggressive infection control by controlling other co-morbidities.

Secondary fractures: Secondary fractures along osteotomy sites are a potential complication of bone transport procedures. Among no patients in the 98-case series, though, was there a tibial fracture during the 3 months after surgery. This would suggest that careful surgical technique, prudent distraction protocols, and patient conformity can reliably eliminate this risk.

Skin necrosis: Soft tissue necrosis over the anterior tibia is another warning that has been seen in the context of TTT. This is typically a secondary complication to tension on the soft tissues and should be addressed with careful surgical planning and postoperative management.[2]

Mortality: Among no patients out of the 98-patient study tragically died during the follow-up period. But these fatalities may occur as a result of disastrous perioperative complications, i.e., myocardial infarct/gastrointestinal hemorrhage and cerebral hemorrhage. These examples are representative of the inherent frailty and severe systemic comorbidities inherent in this group, but not a result of the TTT process in itself.

Ulcer recurrence: Fortuitously, there were no instances of ulcer recurrences were seen in the 98-patient study during follow-up. This suggests that the long-term vascular benefit and tissue regeneration induced by TTT can lead to longer lasting wound healing than usual with conventional techniques.

The rates of complications noted, although present, are apparently quite low given the extent of comorbidities and the advanced nature of the disease of treated patients. The successful elimination of pin tract infection and absence of tibial fracture in the larger study, despite these being recognized risks, show that careful technique and strict care of the patient can successfully reduce such complications. The frequency of post-TTT amputations indicates that TTT, whilst immensely potent, is merely part of a worldwide regimen of treatment and does not inherently rule out limb loss when faced with overwhelming, uncontrolled infection.[6]

Criteria for patient selection and contraindications

Patient selection is important to gain the optimal outcome of TTT with less risk.

Indications: TTT is primarily indicated in non-healing ischemic ulcers, particularly in those with a diagnosis of critical limb ischemia (CLI) and who have high amputation risk. It is especially indicated when conventional treatments, such as routine vascular interventions, fail to heal or are inadequate. The procedure is also reserved for diabetic foot ulcers that are refractory, wherein other interventions have proven ineffective.[1]

Contraindications: There are certain conditions of patients that preclude the safe and effective application of TTT:

Those who have life-threatening illness within the past 3 months or who are medically unstable and unable to tolerate surgery and anesthetic techniques. This emphasizes the necessity of a thorough preoperative medical evaluation.

Tibial osteomyelitis at the planned site of osteotomy. Though successful resolution of calcaneal osteomyelitis near the ulcer in a single case report eliminated this as a contraindication, contraindication in fact exists for infection at the tibial incision site and will compromise osteotomy and fixation. The area of tibial incision with visible wounds, lesions, or active infections within a radius of 5 cm. This is necessary to prevent field contamination and ensuing complications.

The apparent patient selection and contraindications emphasize the requirement of proper patient evaluation before TTT. While highly successful, the procedure is not for all patients and necessitates patients to possess sufficient medical stability to endure both the surgical operation and the extended time of external fixation. The contrast in that osteomyelitis is contraindicated at the location of tibial osteotomy but successfully managed when distal in the calcaneus highlights the need for precise surgical planning and case-by-case evaluation of risk in the patient.[8]

Conclusion: TTT as a promising treatment for refractory DFUs

Overview of TTT's Contribution to Enhanced Outcomes in Dysvascularized Feet

The Tibial Transverse Technique, by its innovative application of Ilizarov's tension-stress principles, constitutes a significant breakthrough in the challenging management of non-healing diabetic foot ulcers complicated by peripheral vascular disease. Its new mechanism of action. through active stimulation of angiogenesis, reconstitution of the microcirculation, and induction of massive tissue regeneration, directly confronts the underlying pathologic deprivations of ischemia and impaired wound healing inherent in such challenging cases.

Clinical evidence, founded on good studies and good case reports, consistently exhibit TTT's very good efficacy. It is excellent for wound healing, objectively improves important vascular parameters such as Ankle-Brachial Index (ABI), WIFi grading, and Transcutaneous Oxygen Measurement (TcPO2), and, above all, leads to very high limb salvage rates. These combined effects stop the progression of gangrene and avoid amputations of the extremity, possibly averting death in patients otherwise destined for certain loss of limb. The success of TTT in an amputation risk population is what makes it revolutionary treatment, giving one hope where traditional vascular and wound care interventions have failed. Its ability to form new vascularity rather than bypassing or dilating pre-existing diseased vessels imparts a unique utility in diffuse microvascular disease seen with diabetes, making traditional revascularization not possible.[8,11]

Future directions and research implications

While evidence for TTT thus far is extremely encouraging, additional high-quality research is required to place it in clinical practice guidelines and more critically evaluate its long-term outcomes and cost-effectiveness in comparison to other newer limb salvage technologies. Large population randomized controlled trials are required to attain the highest level of evidence.

Research in the future needs to be guided along the following principal directions: Refining inclusion criteria to select patients who are most likely to benefit from TTT, developing and refining existing distraction protocols for maximum efficacy and minimum treatment time, and elucidating the synergistic benefit of adjunctive therapies, i.e., particular growth factors or stem cell therapies, in combination with TTT.[3]

These studies could potentially increase the effectiveness of the technique even further and expand its application to an even greater number of patients. In addition, long-term follow-up is necessary to establish limb salvage duration, complication incidence late, and ulcer recurrence risk, to determine the long-term usefulness of this new therapy. While current results are promising, the need for larger and higher-grade trials represents the need to take TTT from an experimental, too often "last-ditch" therapy to a more conventional and standard therapy with more clinical integration and development potential.

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Conflicts of interest

The author declares that there are no conflicts of interest.

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