CASE REPORT

Managing Distal Tibial Fracture Nonunion Using Custom-Made Three-Dimensional Titanium Cage: A Rare Case Report

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Abstract

This case report evaluated the effectiveness of a patient-specific, three-dimensional titanium cage in achieving stable fixation and functional recovery for a complex distal tibial nonunion with extensive bone loss. A 45-year-old male, who sustained a severe nonunion due to high-energy trauma, underwent implantation of a custom-designed titanium cage, which was created using high-resolution CT imaging to ensure a precise anatomical fit. The titanium cage, in combination with a retrograde intramedullary nail and composite bone grafts, provided enhanced structural support and facilitated osseointegration. Thirteen months postoperatively, the patient exhibited minimal pain, full weight-bearing capability, and complete functional recovery. Radiographic evaluations confirmed stable fusion and effective osseointegration, restoring both limb alignment and structural integrity. This case highlights the potential of customized 3D-printed titanium cages for reconstructing significant bone defects in weight-bearing regions, offering a promising solution for complex fractures with severe bone loss by providing structural stability, biocompatibility, and improved clinical outcomes.

Level of evidence: V

Keywords: Bone defect reconstruction, Custom titanium cage, Distal tibia nonunion, Osseointegration, Tibiotalocalcaneal arthrodesis

Introduction

The management of segmental tibial and talar bone loss presents a significant clinical challenge, particularly in cases arising from failed total ankle arthroplasty (TAA), extensive avascular necrosis of the talus, or severe comminuted or open fractures. These cases are often associated with considerable morbidity and complex reconstructive demands, frequently leading to suboptimal clinical outcomes.[1] Various surgical techniques have been investigated to address these extensive bone defects, including bone segment transport with external fixation, tibiotalocalcaneal (TTC) arthrodesis with intentional shortening, and the use of allograft or autograft spacers, as well as talectomy.[2-4] TTC arthrodesis with allograft application is commonly employed for managing extensive tibial and talar defects; however, it is associated with increased risks of disease transmission, graft collapse, and nonunion.[1,5-7]

Although titanium cages are not traditionally used outside of spinal surgery, recent studies suggest they may serve as a viable option for reconstructing large bone defects in the tibia and talus. For example, Attias and Lindsey reported the successful use of a titanium cage in reconstructing a significant tibial defect, emphasizing its potential to reduce the risk of nonunion due to its stability and structural properties.[8] The application of porous titanium cages, which can be packed with osteogenic graft materials, has also shown promise in enhancing bone integration and structural stability in complex reconstructions.[9] Despite these advancements, autografts and allografts present inherent disadvantages, including prolonged operative time required for harvesting, technical challenges in patient positioning and graft shaping, as well as the risks of graft resorption and failure.[10]

In the present case, a complex segmental bone defect in

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the foot and ankle was effectively managed using a multidisciplinary approach that incorporated a titanium cylindrical mesh cage, composite bone grafts, and a locked intramedullary nail to promote osseointegration and structural stability. This approach offers a promising alternative for reconstructing extensive bone defects in the lower extremity, highlighting the potential of titanium mesh cages to support complex orthopedic reconstructions and providing valuable insights for the future management of severe bone loss in the foot and ankle.

Case Presentation

A 45-year-old male presented to our institution four months after sustaining a high-energy motor vehicle accident, which resulted in open fractures of the left tibial plafond and fibula [Figure 1]. The patient had initially received treatment at an external facility, where a spanning ankle external fixator was applied, and both intravenous and oral antibiotic therapies were administered. A wound vacuum-assisted closure (VAC) device was utilized to manage a significant soft-tissue defect on the medial aspect of the distal tibia [Figure 2].

Upon primary assessment at our institution, the patient exhibited signs of severe infection, progressive pain, deformity, and abnormal mobility at the fracture site. Based on these findings, two surgical debridements were performed, and intravenous (IV) antibiotic therapy was initiated. Following an additional three-month observation period and after a thorough review of the patient's extensive treatment history and his expressed desire for limb salvage, a novel surgical approach was undertaken. Informed consent was obtained from the patient, and institutional review board (IRB) approval was granted for the single-patient application of a custom 3D-printed titanium truss cage. This device was specifically designed to address the patient's large segmental bone defect and was used in conjunction with tibiotalocalcaneal (TTC) arthrodesis, utilizing a retrograde intramedullary nail.

Figure 1. X-ray of patient immediately after the trauma in another hospital

Figure 2. X-ray of patient in our hospital

Custom Cage Design Process

The customized gyroid tibial cage was developed through a precise design process that utilized anatomical data from high-resolution (1 mm) computed tomography (CT) scans of both tibias and ankle joints, enabling accurate bone segmentation and defect mapping [Figure 3]. Using the unaffected tibia as a reference, a mirrored reconstruction of the bones was created to serve as a template for the prosthesis. The length and initial design of the cage were then registered onto the defective bone to ensure an anatomical fit. Given that the tibiotalar joint was compromised, an intramedullary channel with a 12 mm diameter was incorporated into the design to facilitate the insertion of a tibiotalocalcaneal (TTC) nail, allowing for postoperative compression across the joint surfaces.

Figure 3. 3D segmented bone

A primary objective of this prosthesis was to preserve limb length, thereby avoiding limb shortening. A porous gyroid lattice structure with a pore size of 400 μm was incorporated to promote osseointegration and facilitate bone ingrowth. Literature has demonstrated that titanium implants with gyroid structures of this pore size enhance bone cell proliferation and osteointegration, thereby optimizing the stability and longevity of the implant. The internal architecture of the gyroid pattern is designed to support cell adhesion and vascularization—key factors for successful bone regeneration and implant integration.

In consultation with the attending surgeon, a modular design was selected for the prosthesis to facilitate intraoperative adjustments. This modularity enables the surgical team to customize the prosthesis configuration based on real-time factors, including ligament laxity, bone loss, and the specific anatomical requirements of the defect. Such an adaptable approach allows adjustments to the number of components and their height, ensuring an optimal and stable fit within the reconstructed joint. This design represents a tailored solution that addresses the complexities of limb salvage surgery, providing flexibility during surgical application.

Surgical Procedure

The surgical intervention required meticulous dissection through extensive scar tissue and hypertrophic nonunion to access the tibial defect. Careful mobilization of the surrounding tissues was performed, followed by a posterior fasciotomy and release of the flexor hallucis longus and flexor digitorum longus muscles to address the soft tissue contracture and ensure adequate exposure [Figure 4a]. Intraoperative fluoroscopy was utilized to accurately localize the nonunion, and a distal tibial osteotomy was carried out using a ½ osteotome and saw. The nonunion site was then carefully debrided to remove non-viable tissue until healthy, bleeding bone was exposed on both sides of the osteotomy [Figure 4b].

A custom-designed titanium cage was positioned within the bony defect, and a retrograde tibiotalocalcaneal (TTC) nail was subsequently inserted to provide compression and mechanical stability across the joint surfaces. To minimize the risk of infection and promote osseointegration, an autograft from the patient's iliac crest was combined with synthetic demineralized bone matrix (DBM) and 2 grams of vancomycin. This composite graft was then packed into the titanium cage prior to its final placement in the distal tibial defect, with fluoroscopic imaging confirming proper alignment and positioning [Figure 4c]. Closure was performed in layers, with the Achilles tendon sheath repaired using 2-0 polyester sutures, followed by sequential closure of the subcutaneous and skin layers. The procedure concluded with the application of a well-padded splint in neutral alignment to immobilize the joint [Figure 5].

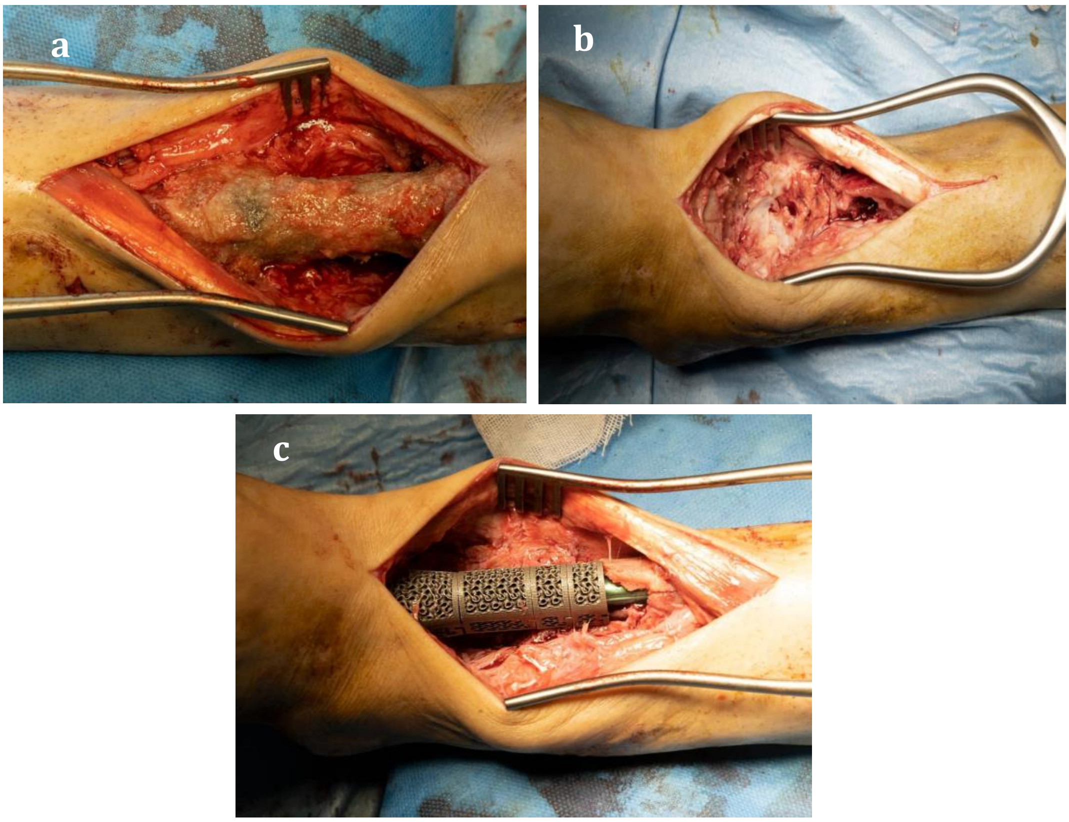

Figure 4. Surgical processes a) nonunion distal tibia b) empty space after debridement of infected bone c) placing custom cage

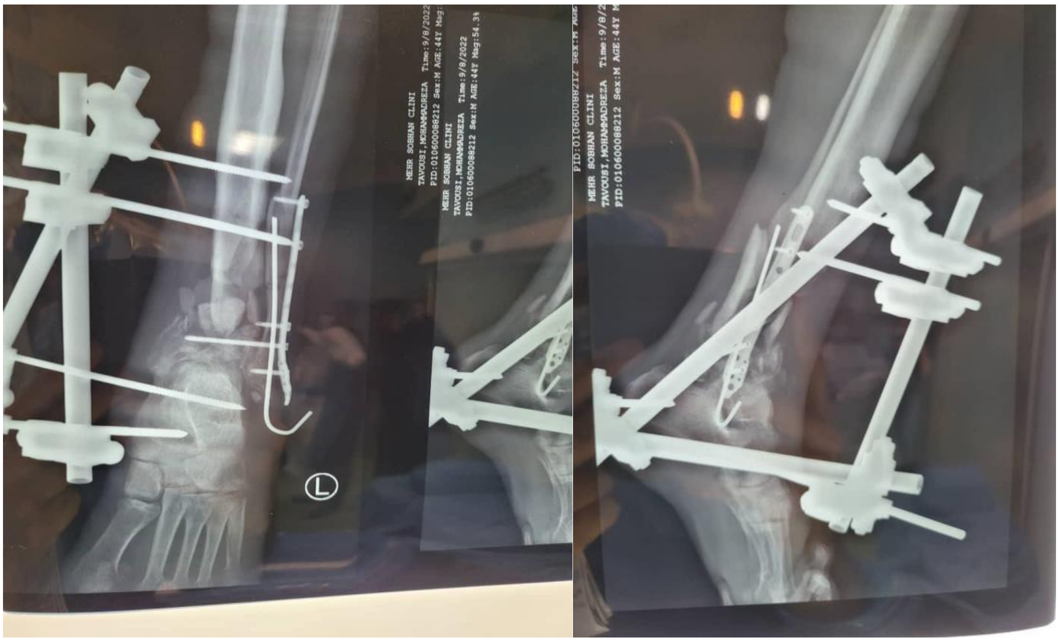

Figure 5. Early post op X-ray

Postoperative Course and Follow-up

Two weeks postoperatively, the incision exhibited satisfactory healing, and the sutures were removed. A non-weight-bearing short leg cast was then applied to maintain alignment and facilitate initial osseointegration. At the two-month follow-up, the patient demonstrated stable alignment with 50% weight-bearing ambulation in a walking cast, without any evidence of hardware migration or malalignment. By the three-month postoperative mark, the patient had progressed to full weight-bearing ambulation. Radiographs and computed tomography (CT) imaging obtained at five months revealed favorable consolidation of the fusion site around the titanium cage, with maintained alignment and stable fixation of the TTC nail.

At 13 months postoperatively, the patient reported minimal pain, no wound complications, and complete independence in ambulation and work without the use of assistive devices. Follow-up standing ankle radiographs demonstrated continued consolidation of the fusion, with stable fixation of the titanium cage and TTC nail in the appropriate anatomical alignment [Figure 6]. The successful outcome observed in this case supports the effectiveness of utilizing a custom titanium cage and TTC arthrodesis for complex tibial defects, providing a viable option for limb salvage in cases of significant bone loss.

Figure 6. X-ray in 13 months after the surgery follow up

Discussion

Managing large bone defects in the ankle remains a complex surgical challenge, particularly due to the high demands for structural stability, restoration of limb function, and prevention of complications. The use of grafts, including autografts and allografts, has proven effective in reconstructing significant bone loss, providing structural support, and stimulating new bone formation through osteoinductive and osteoconductive processes.[3,4] Autografts, derived from the patient's own bone, are valued for their inherent compatibility and osteogenic properties, promoting robust bone healing by delivering live cells and growth factors directly to the site of the defect. However, despite these advantages, autografts have substantial limitations when addressing extensive defects in load-bearing areas such as the ankle.

One critical challenge with autografts is the limited quantity of bone available for harvest, particularly in cases of extensive defects where a substantial volume of graft material is required. Harvesting sufficient autograft tissue from areas such as the iliac crest can lead to structural compromise at the donor site, increasing the risk of pain, weakened bone, and susceptibility to fractures. Additionally, studies have highlighted wound-related complications at the donor site, which contribute to increased morbidity and potentially longer recovery times for patients.[3,11]

For patients who have sustained significant trauma or are undergoing complex reconstructive surgeries, these limitations can hinder the success of autograft applications, as the available graft material may be insufficient to adequately fill and support the defect, thereby compromising structural integrity and clinical outcomes.

Allografts offer an alternative by providing the necessary volume of graft material without the drawbacks associated with donor site morbidity. However, allografts also present specific challenges. They lack the osteogenic potential of autografts, as they do not contain live cells; instead, they rely on osteoconductive and, to a lesser extent, osteoinductive properties to integrate with the host bone. Despite their widespread use, allografts carry inherent risks, including the potential for disease transmission, immune-mediated rejection, and an increased likelihood of structural collapse over time. Studies have shown that allografts, particularly when combined with retrograde intramedullary nails, are associated with nonunion rates as high as 50%, posing significant challenges in achieving stable and durable fusions.[1,11] Given these limitations, there is a clear need for alternative solutions that provide structural stability, minimize infection and rejection risks, and can withstand the stresses of weight-bearing.

In response to these challenges, customized 3D-printed cages have gained attention as an effective solution for managing extensive bone defects, particularly in the ankle and foot, where stability and precise anatomical alignment are critical.[12] 3D-printed cages enable tailored designs based on the patient's unique anatomical structures, providing a customized solution for irregular or large defects.[13,14] The 3D printing process enables the incorporation of complex lattice structures that enhance osseointegration by creating a scaffold conducive to bone ingrowth and vascularization. Notably, the use of titanium and tantalum, materials known for their high biocompatibility, mechanical strength, and corrosion resistance, further improves the durability of these cages in load-bearing applications.[15,16]

Titanium and tantalum have been shown to maintain stability under the mechanical forces exerted during weight-bearing activities, preventing implant collapse and preserving alignment, particularly in cases where gaps exist between bone fragments. Customized titanium cages have demonstrated particular efficacy in tibiotalocalcaneal (TTC) arthrodesis for severe ankle trauma. Studies have documented instances where titanium cages were effectively used to address substantial bone loss, nonunion, and deformity correction in complex reconstructions. Hsu et al. reported a case involving a 63-year-old patient with nonunion and progressive deformity following an open distal tibial fracture, which had been managed with external fixation for one year. The application of a titanium cage allowed for effective stabilization and alignment correction, facilitating limb salvage in this challenging clinical scenario.[17] Similarly, Hamid et al. presented a case involving significant distal tibial bone loss and avascular necrosis of the talus, where the use of a titanium cage in a TTC arthrodesis allowed the patient to resume daily activities with minimal pain after one year. This case highlights the effectiveness of titanium cages in limb salvage procedures for patients with severe bone loss.[18] Mulhern et al. also described successful outcomes using a titanium truss cage in a patient with a failed total ankle arthroplasty, where the patient reported satisfactory pain levels and functional recovery at 30 weeks postoperatively.[15] The versatility of 3D-printed cages in addressing various indications was further supported by a case series conducted by Bejarano-Pineda et al. This study evaluated the effectiveness of 3D-printed titanium cages in TTC arthrodesis using retrograde intramedullary nails across a cohort of seven patients. The indications for TTC arthrodesis in these patients included failed total ankle arthroplasty (TAA) in two cases, extensive avascular necrosis of the talus in two cases, nonunion following ankle arthrodesis in one case, and severe tibial/talar fractures in two cases. Favorable outcomes were reported, with 85% of patients demonstrating over 50% bony bridging at the fusion site. This high rate of bone fusion suggests a strong potential for these cages to facilitate stable fusion and integration in complex, large bone defects.[19] Such results indicate successful fusion of the bones involved in the arthrodesis procedure.

Additionally, the pain and complications associated with autograft harvesting further underscore the benefits of 3D-printed cages. A study by James et al. found that 27% of patients who underwent foot and ankle surgery with autografts harvested from the anterior ilium reported greater pain at the graft harvest site than at the surgical site, highlighting the morbidity associated with autograft harvesting.[17] This study did not involve autograft harvesting, which likely contributed to patient satisfaction and minimized the morbidity associated with secondary surgical sites. By eliminating the need for autograft harvesting, 3D-printed gyroid cages or Triply Periodic Minimal Surface (TPMS)-structured prostheses offer an appealing alternative. These prostheses avoid the painful and risky complications of donor site morbidity while potentially enhancing fusion stability through optimized pore structures and tailored material properties.[11,20]

A notable limitation of this article is the lack of a large, controlled patient sample, as it primarily focuses on individual case studies and a limited case series. This small sample size restricts the generalizability of the findings and makes it challenging to establish the broader applicability of 3D-printed titanium cages for extensive ankle bone defects. Additionally, while the use of customized cages shows promise, there is limited longitudinal data on the durability and long-term outcomes associated with these implants, including potential complications such as late-onset implant loosening, bone resorption, or mechanical failure. Further large-scale, multi-center studies with extended follow-up are necessary to assess the consistency of outcomes and gain a deeper understanding of the potential risks associated with this approach.

Overall, the use of customized 3D-printed cages represents an innovative and effective approach for managing large and complex bone defects in the ankle. These cages offer the benefits of precise anatomical customization, high mechanical strength, and the ability to promote osseointegration, providing an effective alternative to traditional autografts and allografts in patients where donor site complications, infection risks, and structural stability are significant concerns. The success of 3D-printed cages in clinical cases suggests that they can serve as a primary solution for limb salvage and complex bone reconstruction, supporting functional outcomes and enhancing the quality of life in patients with challenging bone defects.

Conclusion

Customized 3D-printed cages offer several advantages over traditional grafting techniques for extensive ankle bone defects, including improved structural stability, enhanced biocompatibility, and reduced donor site morbidity. These cages enable individualized design tailored to the patient's anatomy, addressing both functional and anatomical challenges, and providing a promising solution for cases requiring limb salvage and complex joint reconstruction.

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