CURRENT CONCEPTS REVIEW

Optimizing Outcomes after Operative Treatment Bicondylar Tibial Plateau Fractures – Time for Innovation?

Mihir S. Dekhne, MD; Derek Stenquist, MD; Nishant Suneja, MD; Michael J. Weaver, MD; Michael Moerk Petersen, MD, DMSc; Upender Martin Singh, MD; Arvind Von Keudell, MD, MPH

Research performed at Harvard Medical School Trauma Initiative/Brigham and Women's Hospital and Rigshopsitalet, Copenhagen, Denmark

Received: 5 June 2023 *Accepted: 30 October 2023*

Abstract

Bicondylar tibial plateau fractures are technically demanding fractures that have a high complication rate. We sought to review the recent literature with the aim to summarize the development of new classification systems that may enhance the surgeon's understanding of the fracture pattern and injury. We highlight the best methods for infection control and touch on new innovative solutions using 3D printer models and augmented mixed reality to provide potentially personalized solutions for each specific fracture configuration.

Level of evidence: N/A (Narrative review/commentary)

Keywords: Bicondylar, Geriatric, ORIF, Tibial plateau

Introduction

Tibial plateau fractures consist of 1% of all fractures and can be caused by either low- or high-energy mechanisms of injury. In low-energy injuries, the fractures are usually unilateral, while high-energy injuries tend to have more comminution where both condyles are involved. Furthermore, high-energy fractures often involve severe damage to soft tissues and neuro vasculature, which can impact treatment choices.[1–4]

Bicondylar tibial plateau fractures (BTPs) are a type of injury that is high-energy in younger individuals and low-energy in older people. They involve both the medial and lateral articular surfaces, along with the metaphyseal articular fragments being disrupted. BTPs make up around 18-39% of all tibial plateau fractures and frequently are associated with soft tissue damage such as meniscal or ligamentous injuries. Ligamentous injuries can occur in up to 80% (43-80%), meniscal tears up to 22%, and acute compartment syndrome in 3-27%.[5–13]

Operatively treated BTPs have been reported to have a high overall complication rate (up to 39%).[14–17] Common complications include deep infection, malunion, or non-union requiring re-operation. These complications may be more prevalent in bicondylar fracture patterns due to the degree of articular comminution, a greater degree of soft tissue trauma, and multiplanar deformity requiring dual incision or dual plating techniques. Notwithstanding, BTPs are complex injuries with profound morbidity.[6,16–24]

Despite the complexity of these injuries and their high complications, the optimal management of BTPs remains debated. Here, we review the clinical evaluation, imaging, and classification systems of bicondylar tibial plateau fractures with a focus on surgical management before providing specific tips on how to minimize complications and optimize clinical outcomes. This review highlights highly debated issues related to complex bicondylar tibial plateau fractures such as the timing of surgical fixation, single versus dual plating, 3-D imaging, and virtual reality applications.

Materials and Methods

The literature search for this narrative review was conducted through electronic databases, including PubMed, Scopus, and Web of Science. A comprehensive search was performed to identify relevant articles, reviews, and primary studies published up to 1/1/2022. The search terms included "bicondylar tibial plateau fractures", "tibial plateau fractures", "knee fractures" and "innovation" to ensure a

Corresponding Author: Arvind Von Keudell, Harvard Orthopaedic Trauma Initiative, Harvard Medical School, Boston, Massachusetts, USA/ Department of Orthopaedic Surgery, Brigham and Women's Hospital, Boston, Massachusetts, USA/ Department of Orthopaedic Surgery, Rigshospitalet, Copenhagen University Hospital, Copenhagen, Denmark

Email: avkeudell@gmail.com

THE ONLINE VERSION OF THIS ARTICLE ABJS.MUMS.AC.IR

broad exploration of the topic. Inclusion and Exclusion Criteria: Articles were included based on their relevance to the review's focus on bicondylar tibial plateau fractures. Inclusion criteria encompassed studies that provided valuable insights, theoretical frameworks, historical perspectives, and contemporary discussions on the subject matter. Exclusion criteria involved articles that were not pertinent to the scope of the review or lacked credibility. Data Extraction: Information was extracted from selected studies, including key findings, methodologies, and theoretical frameworks. The narrative synthesis aimed to integrate diverse perspectives, historical developments, and current debates on the topic. Data extraction was performed independently by AVK and MD, and any discrepancies were resolved through discussion. Quality Assessment: A critical appraisal of the selected literature was conducted to assess the quality and reliability of the included studies. The assessment considered factors such as study design, methodology, sample size, and the credibility of sources. While the focus was on synthesizing a narrative rather than conducting a formal systematic review, this critical evaluation ensured a thoughtful consideration of the reviewed literature.

Results

Clinical Evaluation

History

A detailed history is critical to discern the mechanism of injury, as the character of the fracture depends on both the energy of the trauma and the direction of force applied to the limb. Motor vehicle collisions, falls from height, pedestrians struck by vehicles and motorcycle accidents are the most common injury mechnisms.[17,20] In general, higher-energy trauma is associated with more complex fracture patterns and poorer prognosis. However, low-energy mechanisms combined with osteoporotic bone can similarly lead to complex fracture patterns. In either case, one must carefully evaluate each patient to understand fracture personality, predict concomitant injuries, and anticipate soft-tissue complications.

Many papers have identified comorbidities such as diabetes and smoking status as risk factors for increased length of stay, readmission rates, and higher rates of deep infection, respectively.[17,20,22]

Physical Exam

As many of the complications encountered when treated BTPs relate to wound issues or infection a thorough and careful evaluation of the skin and soft tissues is important. Particularly, the anteromedial surface of the proximal tibia does not provide a lot of soft tissue and can be an area of skin infection or necrosis. There is currently no standardized measure of assessing skin integrity to determine early vs. delayed definitive management. Blistering can give clues to the underlying trauma and often require a delay in definitive treatment.

The presence of open wounds may indicate an open fracture. In these cases, immediate antibiotic treatment and thorough surgical debridement is indicated to decrease the rate of infection.

It's crucial to conduct a comprehensive neurovascular evaluation of the affected limb promptly. Injuries to the peroneal nerve caused by stretching are more common with medial plateau and high-energy fractures.[25] Observing differences in pulses compared to the contralateral extremity can suggest potential arterial injuries. When there is clinical suspicion for arterial injury in an apparently perfused limb, obtaining ankle brachial indices (ABI) followed by CT angiography can be helpful. However, if there are clear indications of leg ischemia, it's crucial not to postpone vascular exploration and subsequent revascularization.

There is also a high incidence of compartment syndrome in BTPs (up to 30%) with some fracture patterns having an even higher risk. When the patient presents with severe pain or pain with passive stretch or pain out of proportion, emergent fasciotomy should be performed. In a patient with an unreliable exam, compartment pressures can provide another data point in the evaluation of acute compartment syndrome. If the initial evaluation is normal, It is important to perform repeated serial examinations of the leg compartments because compartment syndrome can manifest 24 hours or even more after the initial injury. Missed compartment syndrome can cause severe disability including nerve and muscle damage.[6,17,18,20,26–30] In severe cases, an amputation is required. Neurological symptoms may indicate already an advanced stage of acute compartment syndrome and should prompt an emergent fasciotomy.

Radiographic and Advanced Imaging

To evaluate coronal and sagittal alignment, axial stability, and the degree of comminution, itis essential to take orthogonal radiographs centered on the knee. The AP view can reveal compression or depression of the articular surface and allows inspection of the tibial spines. The lateral view can demonstrate posteromedial fracture lines or coronal split plane fractures that are otherwise poorly visualized on AP imaging. In high-energy fractures with significant comminution, other imaging modalities are required to supplement plain radiographs. It is important to critically analyze the injury radiographs as they provide clues to the mechanism of injury and deforming forces.

Computed tomography (CT) provides a more reliable assessment of articular depression and comminution, along with a detailed delineation of fracture patterns for surgical planning. Thin-cut CT scans with sagittal and coronal reconstructions are routinely obtained as articular depression is often underappreciated on plain radiographs and may alter fracture classification.[31,32] Furthermore, CT may also give clues to posteromedial or posterolateral fracture patterns that require specific fixation by understanding the degree and exact location of a depressed and comminuted fragment. The utilization of 3D reformatted images is particularly useful in planning fracture surgery and in helping to determine the ideal placement of plates.

Magnetic resonance imaging (MRI) remains the most sensitive modality to diagnose ligamentous injury, meniscal pathology, or cartilaginous damage.

However, MRI has not been found to change surgical treatment plans or improve clinical outcomes in tibial plateau fractures. [8]

Classification Systems

Several classification systems are available to describe tibial plateau fractures; however, none of them is universally accepted, ideal, or comprehensive enough to cover all fracture morphologies.[33,34] The two most frequently used systems to classify tibial plateau fractures are the Schatzker classification and the AO/OTA classification.

Schatzker Classification

The Schatzker classification, based on X-rays, is the most commonly used system in North America for describing fracture patterns, which relies on orthogonal radiographs. It generally describes types I through IV as unicondylar fractures, type V as bicondylar fractures with an intact metaphysis, and type VI as bicondylar fractures with metaphyseal disruption. It fails to capture various fracture features that have significant treatment implications such as presence of posteromedial or posterolateral fractures.

AO-OTA Classification

The AO-OTA classification system for tibial plateau fractures (AO 41) differentiates between extraarticular (A), partial articular (B), and complete articular (C) fractures. Although the AO classification provides more detailed information about fracture patterns than the Schatzker system, it does not offer any guidance on the best treatment options for specific fractures.

Column System

More recently, a CT-based 3-column classification system has been developed that divides the axial view of the tibial plateau into three columns: anterolateral, anteromedial, and posterior.[35,36] In this system, fractures are categorized as 0, 1, 2, or 3-column injuries. BTPs are either 2- or 3-column injuries, with the most common 3-column fracture being the Type V/VI Schatzker BTP combined with a separate posterolateral articular fragment.

Importantly, analyses of BTPs through the lens of the 3-column system have revealed the presence of a posteromedial fragment in nearly two-thirds of fractures. The knowledge of these posteromedial and posterolateral fragments, combined with the 3-column framework, has changed the understanding of BTPs and strategies for treatment. The main concept is to provide surgeons with principles that may assist in deciding where to place the buttress plate (thumb pressure), what surgical approach is therefore needed, and how to achieve articular congruity and joint stability.

Treatment

Goals

In the majority of cases, the primary objective of treatment is to achieve an anatomic reduction of the tibial articular surface and to restore normal knee alignment, with normal condylar widths. This is particularly important in the coronal plane (varus/valgus), as it reduces the risk of developing post-traumatic arthritis. The impact of the sagittal plane (tibial slope modification) on outcomes is less clear and has been less extensively studied. Stable fixation that allows for early mobilization is crucial to prevent post-traumatic stiffness. the goal of surgical fixation is the restoration of leg alignment in the coronal and sagittal planes. [4,24]

Due to the complex nature of bicondylar plateau fractures, there is no one-size-fits-all approach to operative treatment. A range of techniques have been described, but the optimal strategy must be tailored to individual patient factors, including bone quality, fracture pattern, and concomitant injuries. Surgeons must weigh the importance of achieving an anatomic reduction of the articular surface with stable internal fixation against the risks associated with soft tissue injury, wound complications, and infection. The complication rate of BTPs can be as high as 50%, underscoring the significant challenges of managing these injuries.[4,17]

Indications

There is currently no clear consensus that have established the indications for surgical intervention in cases of bicondylar tibial plateau fractures. However, often-mentioned criteria for operative management include articular incongruity, malalignment, and joint instability. The importance of restoring articular congruency remains uncertain, as low rates of severe arthrosis have been observed in patients with mild-to-moderate articular displacement.[37–41] There is some evidence that articular step-off up to 5mm has not affected clinical outcome. The condylar width should be restored to its normal anatomy. [3] Instability and coronal malalignment have been shown to predict poorer outcomes; any degree of varus malalignment and >5° of valgus malalignment, along with instability to stress, should indicate patients for operative management.[3,40,42–45]

Timing of Surgery

There is currently insufficient evidence to determine the optimal timing for fixation of bicondylar tibial plateau fractures, as studies have shown high rates of infection and reoperation regardless of whether surgery is staged or performed as a single procedure.[13,20] Soft tissue blistering and the mechanism of injury can certainly indicate the amount of underlying soft tissue injury, but it is currently hard to quantify and correlate these observations with the risk of infection and re-operation. Traditionally, a staged approach (temporary bridging external fixation followed by definitive ORIF) has been recommended to allow for soft tissue recovery.[46] However, some reports indicate that patients that are placed into an external fixator have a higher risk of re-operation.[14,47] Recent evidence suggests that non-staged surgery performed by experienced orthopaedic trauma surgeons within 72 hours from injury is safe and can achieve a satisfactory reduction in a large proportion of bicondylar tibial plateau fractures, provided the soft tissues allow[48,49] Several studies have shown that early single-stage treatment of bicondylar tibial plateau fractures can be cost-effective and safe if the patients are appropriately selected.[50] There is currently no agreement among experts on the optimal timing of definitive fixation with regard to fasciotomy closure in cases of compartment syndrome.[29,30,51]

The lack of clear guidelines in regard to the timing of definitive surgical fixation allows for multiple various surgical tactics often determined by surgical expert opinions.

In the setting of an open fracture, it is unclear if definitive fracture fixation should be performed at the time of the debridement or should be staged with a period of soft tissue rest in an external fixator. This decision is difficult and depends upon the complexity of the fracture, the required surgical approach(s), the nature of the open wound itself, and the possible need for soft tissue coverage.

Open Reduction Internal Fixation (ORIF)

In cases of axial instability and compromised soft tissue envelope, external fixation and ligamentotaxis can help specifically with improved imaging quality via partial fracture reduction.

Staged ORIF after a period of initial temporizing external fixation can help minimize soft-tissue complications.[47,52,53]

The choice of operative approach for tibial plateau fractures is individualized based on the fracture pattern and soft tissue status. Traditionally, surgeons have used anterolateral or medial approaches. However, recent advancements in understanding fracture morphology and the importance of posteromedial and posterolateral fragments have led to updated strategies. Fixation of these posterior fragments necessitates buttress-plating and/or fixation from posterior to anterior. Determining the appropriate approach(s) requires a detailed understanding of the fracture pattern to allow for both an anatomic reduction of the articular surface and to place fracture implants in the ideal position to neutralize deforming forces.

Extensive description exists for the posteromedial fracture pattern, which if left inadequately fixed can result in poor outcomes and posteromedial instability. In the case of BTPs with a coronal fracture line through the medial tibial condyle, a dual approach is often the preferred treatment option. It should be noted that the use of a medial plate alone in such cases may not provide sufficient fragment stability.[54] Similarly, the use of a lateral locking plate may not achieve an adequate posteromedial fragment fixation.[55–57] Rather, adequate reduction and fixation of the fracture requires a posteromedial approach with a 3.5 mm plate and screw construct to withstand the strong forces on the posteromedial column during gait[58–62] Utilizing the interval between the pes anserinus and medial head of gastrocnemius, the posteromedial approach can be achieved in both supine and prone positions.[63–66] Additional fixation of the remainder of the fracture can usually be achieved through a separate anterolateral approach with a laterally placed plate [Figure 1].

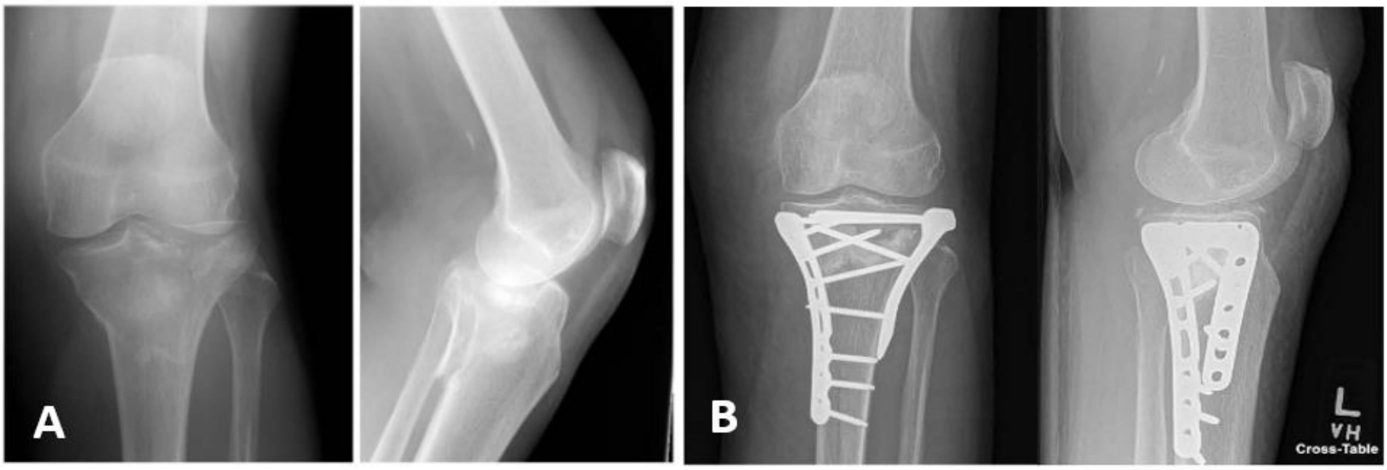

Figure 1. 70-year-old female presented with a Schatzker IV fracture dislocation with lateral impaction injury (A), one year follow-up after bi-condylar tibial plateau plating

Less common than the posteromedial fracture pattern, posterolateral fracture fragments can typically be treated with a standard lateral plating construct. A posterolateral approach with fibular head osteotomy or osteotomy of the lateral epicondyle can allow for simultaneous reduction of the posterolateral fragment and fixation of the lateral column through a single incision, if needed [67] [Figure 2]. This may provide improved maintenance of the reduction of the posterior fragment when compared with an anterolateral approach.[68]

The impact on postoperative outcomes of reduction and fixation posterolateral fractures and how to best stabilize them remains a topic of debate.

Though generally avoided due to the risk of flexion contracture and risk of injury to the neurovascular of the popliteal fossa, the direct posterior approach is also a viable approach. In the setting of coronal fractures with the posterior shear column, or avulsion of the PCL insertion with a fracture line extending into the articular surface, the direct posterior approach may afford the surgeon with improved visualization and control of fracture fragments.

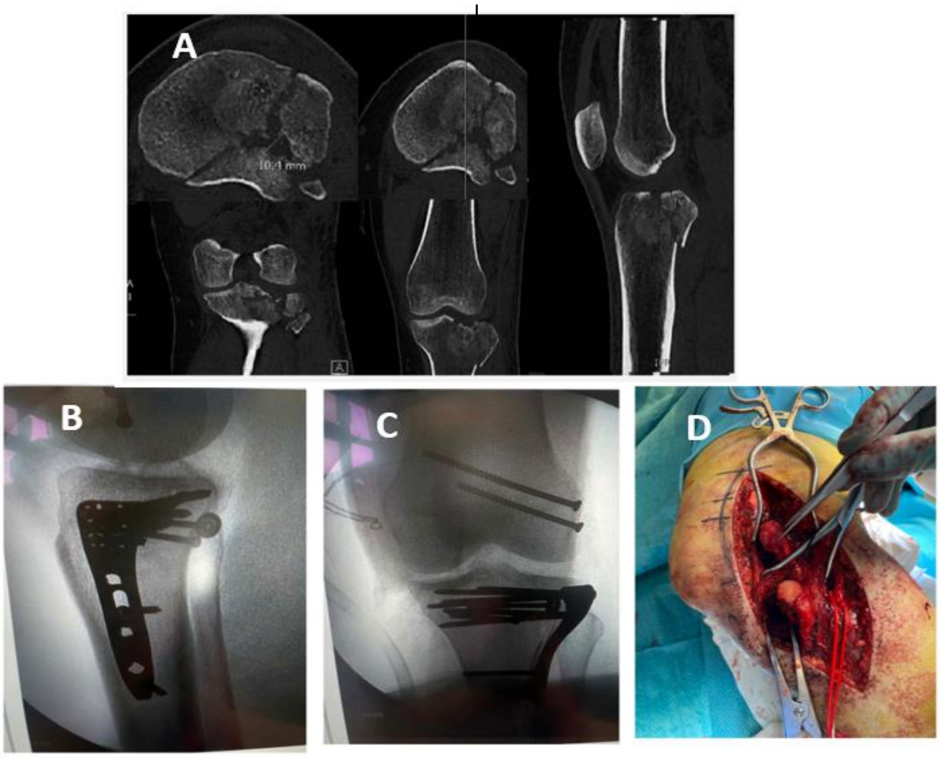

Figure 2. 25-year-old female sustained a posterolateral tibial plateau fracture (A). She was treated through a posterolateral approach in addition to a lateral epicondylar osteotomy. Postoperative lateral (B) and AP view (C) demonstrate good restoration of the tibial plateau with cannulated screw fixation of the posterolateral fragment. (D) Depicts the clinical picture of the approach with the peroneal nerve identified and a reduction clamp applied on the posterolateral fragment behind the fibular head and on the lateral femoral condyle. A laminar spreader was used to open the anterolateral window to elevate depressed articular fracture fragments

Posteromedial or posterolateral fracture fragments are often associated with dislocations of the knee joint. Knee joint dislocations can be put into its anatomic relationship by placing a large per articular clamp in the opposite direction to reverse the knee joint dislocation forces. This often results in indirect reduction of the articular segments and can greatly help with the remainder of the surgical fixation [Figure 3].

Dual Plating vs. Single Lateral Locking Plating

By functioning as a fixed-angle device, a lateral locking plate can keep up (cantilever) the medial condyle from the lateral side and may provide enough stability to forego a separate medial plate in bicondylar fractures.[69–71] However, a lateral locking plate does not always provide adequate stabilization of BTPs. The use of a single locking plate may limit the surgeon's choice of screw placement and direction, and in the setting of a small, comminuted, or osteoporotic medial condyle, may be insufficient to provide adequate support. In these cases, additional medial support is needed to mitigate the risk of developing late varus. From a biological perspective, single plate constructs obviate the need for a second incision limiting the soft tissue insult and thereby theoretically reducing infection risk.[18,72] From a biomechanical perspective, dual plating appears to be superior to single lateral locked plating, particularly in fractures with a posteromedial coronal component.[73–77] However, in clinical studies comparing these methods, no configuration has proven to be consistently superior in terms of fixation or outcomes.[20,56,78,79] Furthermore, dual plating may be associated with a higher rate of infection.[80]

Definitive External/Ring Fixation

Although ORIF provides maximal biomechanical stability through the fracture, compromised soft tissues may preclude definitive internal fixation. The use of hybrid constructs or ring external fixators has been advocated to minimize ORIF complications in the setting of extensive soft tissue disruption.[81] In these constructs, the articular surface is reduced percutaneously and stabilized with subchondral lag screws or wires. After reduction, an external fixator or a hybrid ring fixator is placed for two to four months, allowing knee range of motion and weight-bearing after callus formation. The average healing time for these constructs has been reported as 14 weeks, which is comparable to the healing times observed with plating techniques.[82,83] However, ring fixator treatment is not without complications. In addition to high superficial infection rates

and high malunion rates, ring fixation is associated with substantial malalignment including varus/valgus, articular step-off, and condylar widening.[83–86]

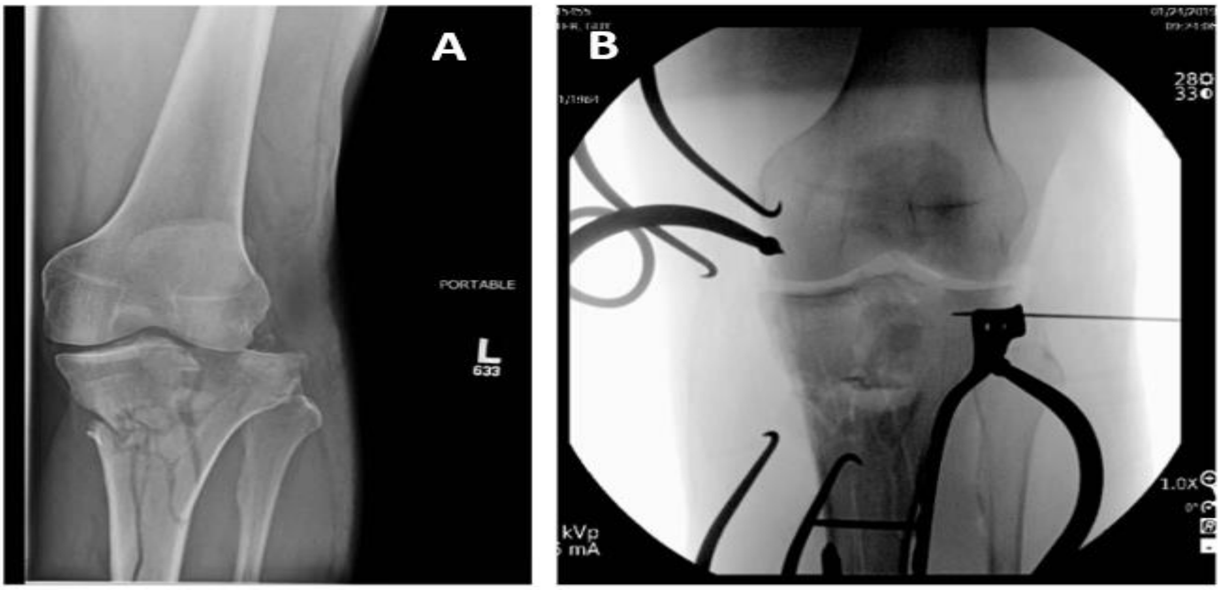

Figure 3. 65-year-old male suffered a Schatsker IV fracture dislocation of the left knee (A), application of a large articular reduction clamp can successfully reduce the fracture dislocation by applying one tine on the medial femoral condyle and the other tine on the lateral tibial plateau (B)

Definitive External/Ring Fixation

Although ORIF provides maximal biomechanical stability through the fracture, compromised soft tissues may preclude definitive internal fixation. The use of hybrid constructs or ring external fixators has been advocated to minimize ORIF complications in the setting of extensive soft tissue disruption.[81] In these constructs, the articular surface is reduced percutaneously and stabilized with subchondral lag screws or wires. After reduction, an external fixator or a hybrid ring fixator is placed for two to four months, allowing knee range of motion and weight-bearing after callus formation. The average healing time for these constructs has been reported as 14 weeks, which is comparable to the healing times observed with plating techniques.[82,83] However, ring fixator treatment is not without complications. In addition to high superficial infection rates and high malunion rates, ring fixation is associated with substantial malalignment including varus/valgus, articular step-off, and condylar widening.[83–86]

Clinical Outcomes

Infection

Soft tissue compromise and devascularization in the setting of high-energy trauma predisposes BTPs to increased rates of infection. Historically, ORIF had been associated with infection rates as high as 10-20%.[24] This risk may be increased with operative times exceeding three hours, regardless of dual vs. single incision approaches.[6]

Mal/ Non-Union

Nonunion are rare in proximal tibial fractures and are very challenging to treat. Malunion is even less well described and studied, however inadequate fixation of posteromedial or posterolateral fractures that are inadequately fixed may lead to instability in flexion. This area requires further research to quantify the impact of malunion on clinical outcomes and conversion to total knee replacement.[87]

Long-Term Outcomes

Given the wide range and severity of BTPs, along with advancements in approaches and surgical management, long-term outcomes are difficult to evaluate. Many studies have shown decreased functional outcomes after ORIF, with higher energy mechanisms of injury being associated with poorer outcomes.[15,88] Further, high-energy injuries have been associated with persistent pain, low rates of return to baseline activity, and higher rates of conversion to total knee arthroplasty (TKA).[88–91] However, the literature also suggests that satisfactory functional outcomes can be obtained with severe injuries. In these studies, few patients were found at early follow-up to require additional surgical intervention, and most demonstrated satisfactory knee function at long-term follow-up.[5,37]

Additionally, the incidence of posttraumatic arthritis remains high in tibial plateau fractures, and particularly in BTPs.[15,37,38,92–94] The risk of developing posttraumatic osteoarthritis may rise with age, meniscectomy, ligamentous instability, and residual tibial plateau malalignement. Nonetheless, there is limited evidence indicating a significant correlation between residual articular step-off and the development of progressive degenerative changes. Furthermore, it appears that the presence of post-traumatic knee arthritis on plain radiographs does not necessarily correspond to poor functional outcomes.[37,39,40,88]

How to Avoid Complications

Infection

Infection rates among tibial plateau fractures remain high due to soft-tissue compromise and devascularization in the setting of high-energy trauma. Nonmodifiable risk factors for postoperative infections include male gender, and the articular injury itself. Modifiable risk factors include smoking and increased operative time. Also, comparative studies have indicated a potential association between dual plating and higher infection rate.[20,80]

A recent study has shown that keeping an external fixator or elements of it in place during the operation does not significantly increase the rates of infection or reoperation. By leaving the external fixator in place prior to definitive fixation, the surgeon may achieve stability and distraction while improving efficiency and decreasing costs.[95]

Perioperative antibiotic prophylaxis is crucial in preventing infections. A randomized controlled trial conducted across multiple centers, called the VANCO trial, showed that the use of intrawound vancomycin during definitive fixation reduced the risk of gram-positive deep surgical site infections, especially in BTP patients with a high risk of infection.[96]

Lastly, as demonstrated by the fluid lavage of open wounds (FLOW) trial, intraoperative irrigation is a simple intervention that may decrease rates of reoperation, infection, wound healing, and nonunion. Importantly, this benefit is independent of irrigation pressure, and may in fact be improved with saline alone when compared to soap.[97]

Compartment Syndrome

Given the subjectivity of clinical examination and differing opinions between examining surgeons (such as palpating the firmness of the compartment), any suspicion of impending compartment syndrome warrants fasciotomy. If after performing fasciotomy of the compartments does not reveal acute compartment syndrome (no bulging), the skin may be closed primarily or partially in the setting of high suspicion. In cases of high-energy trauma, the underlying fascia may already be opened/damaged. In these cases, it might be worthwhile to complete the incision and debridement, followed by secondary closure. Often times when planning for definitive fixation the incisions can be kept separate from each other, i.e. keep fasciotomy incisions slightly distal and anterior and the approaches slightly posterior. This occasionally requires percutaneous fixation of the shaft screws.

Quality of Life

Long-term complications have an impact on patients' quality of life. Likewise, the need for reoperation or conversion to TKA has been reported in up to 14%. [88] The incongruity between patient expectations and clinical prognosis may lead to decreased satisfaction at long-term follow-up.[88] As such, patients with BTPs should be counseled regarding general prognosis along with the need for extensive rehabilitation and/or potential reoperation.

Future Developments

Virtual Reality (VR), Augmented Reality (AR), and Three-Dimensional (3-D) Printing Proximal tibia fractures can be complex and sometimes fracture planes difficult to understand.Despite the spatial visualization provided by preoperative three-dimensional (3D) CT reconstruction, its effectiveness in pre-operative design is constrained due to the two-dimensional (2D) display of individual images at the time of surgery. This limitation makes it challenging to translate the preoperative 3D reconstruction to a 2D intraoperative imaging making an anatomical reduction of fracture fragments during intra-operative procedures slightly more challenging.[98] The proliferation of virtual reality (VR), augmented reality (AR), and three-dimensional (3-D) printing technologies may enable surgeons to leverage improved understanding of the fracture morphology, patient-specific fracture treatment and eventually optimize the treatment of BTPs.

By enabling the overlay of digital images onto the physical world, both Augmented Reality (AR) and Virtual Reality (VR) offer physicians the opportunity to enhance the visualization of intricate fracture configuration. Moreover, these technologies introduce increased levels of interactivity, allowing for a more immersive and engaging experience also between surgeons. The resultant benefits, observed in various specialties outside of orthopaedics, might include reduced operative time, improved clinical outcomes, and increased surgeon confidence. While still in its infancy, early studies show promise for these tools in similarly improving orthopaedic practice.[99,100]

Furthermore, 3-D printed anatomic models are becoming increasingly commonplace in the preoperative planning of many orthopaedic injuries. The advent of on-demand manufacturing of 3D models has made it possible for surgeons to accurately replicate the shape and displacement of fracture fragments before surgery. This enables preoperative simulation operations to be conducted on the 3D fracture model, facilitating precise reduction of fracture fragments, correction of rotation and angulation deformities, and restoration of the anatomical morphology of the proximal tibial structure.[101]

Early studies utilizing this technology in tibial plateau fractures have shown clinical promise, with benefits including reduced operative time, blood loss, and use of intra-operative fluoroscopy along with improved patient-reported outcomes at follow-up.[98,102,103] Although still in its early stages, 3D printing holds the potential to enhance efficiency, optimize reduction techniques, minimize operation time and blood loss, and greatly enhance the surgical, clinical, and radiographic outcomes of traumatic injuries.

In a recent survey 50% of orthopedic trauma surgeons felt that they base their postoperative weight-bearing plan on their gut feeling. Hence, every patient is different, every fracture is different, and every surgeon tackles fractures slightly differently with standard off-the-shelf implants. This leads to a high rate of variability in treatment and outcome. Another avenue for improved understanding might lie in Finite Element Analysis of Fixation constructs that can give insight on the stability. The latest development in this space may lie in using artificial intelligence to segment, reconstruct and plan according to specific fracture lines and calculate the best possible fixation method with existing implants.

This helps might not only the patient to have a reliable rehabilitation with potential earlier weight-bearing but also allows the surgeon to have an objective and planned surgical roadmap.

Conclusion

BTPs represent a high-energy subset of proximal tibia fractures that are often associated with soft-tissue compromise and devascularization, slight malalignment, reoperation and with chronic disability. At present, treatment of bicondylar plateau fractures is guided by the soft tissue envelop, fracture configuration. Anatomic reduction of the articular surface with careful soft tissue handling, and restoration of the mechanical axis of the limb. The advent of locking plates has led to a paradigm shift in fracture fixation, allowing for more stable fixation. This occasionally permits the stabilization of bicondylar fractures with a unilateral approach. The future of articular fixation may be helped by understanding the biomechanics of the construct better, i.e. the most optimal plate and screw placement in addition of intraoperative guidance with 3D printed guides, fracture models and Augmented Reality.

The high incidence of complex complications such as infection, chronic disability, and conversion to TKA associated with this injury underscores the imperative for future innovations.

Acknowledgement

Not applicable

Conflict of interest: None

Funding: None

Mihir S. Dekhne MD [1,2]
Derek Stenquist MD [2]
Nishant Suneja MD [2]
Michael Weaver MD [2]
Michael Moerk Petersen MD, DMSc [3,4]
Upender Martin Singh MD [3]
Arvind Von Keudell MD, MPH [2,3,4,5,6]

1 Harvard Medical School, Boston, Massachusetts, USA
2 Harvard Orthopedic Trauma Initiative, Harvard Medical School, Boston, Massachusetts, USA
3 Department of Orthopedic Surgery, Rigshospitalet, Copenhagen University Hospital, Copenhagen, Denmark
4 Department of Clinical Medicine, Faculty of Health and Medical Sciences, University of Copenhagen, Copenhagen, Denmark
5 Department of Orthopedic Surgery, Brigham and Women's Hospital, Boston, Massachusetts, USA
6 Department of Orthopedic Surgery, Bispebjerg Hospital, Copenhagen University Hospital, Copenhagen, Denmark

References

1. Albuquerque RPE, Hara R, Prado J, Schiavo L, Giordano V, do Amaral NP. Epidemiological study on tibial plateau fractures at a level I trauma center. Acta Ortop Bras. 2013; 21(2):109-115. doi: 10.1590/S1413-78522013000200008.
2. Egol K, Koval KJ, Zuckerman JD,eds. Handbook of Fractures. 5st ed. Lippincott Williams & Wilkins; 2012.
3. Honkonen S, Jarvinen M. Classification of fractures of the tibial condyles. J Bone Joint Surg Br. 1992; 74-B (6):840-847. doi:10.1302/0301-620X.74B6.1447244.
4. Berkson EM, Virkus WW. High-Energy Tibial Plateau Fractures. J Am Acad Orthop Surg. 2006; 14(1):20-31. doi: 10.5435/00124635-200601000-00005.
5. Stannard JP, Wilson TC, Volgas DA, Alonso JE. The less invasive stabilization system in the treatment of complex fractures of the tibial plateau: short-term results. J Orthop Trauma. 2004; 18(8):552-558. doi:10.1097/00005131-200409000-00012.
6. Colman M, Wright A, Gruen G, Siska P, Pape HC, Tarkin I. Prolonged operative time increases infection rate in tibial plateau fractures. Injury. 2013; 44(2):249-252. doi:10.1016/j.injury.2012.10.032.
7. Eggli S, Hartel MJ, Kohl S, Haupt U, Exadaktylos AK, Röder C. Unstable bicondylar tibial plateau fractures: a clinical investigation. J Orthop Trauma. 22(10):673-679. doi:10.1097/BOT.0b013e31818b1452.
8. Stannard JP, Lopez R, Volgas D. Soft tissue injury of the knee after tibial plateau fractures. J Knee Surg. 2010; 23(4):187-192. doi: 10.1055/s-0030-1268694.
9. Mui LW, Engelsohn E, Umans H. Comparison of CT and MRI in patients with tibial plateau fracture: can CT findings predict ligament tear or meniscal injury? Skeletal Radiol. 2007; 36(2):145-151. doi:10.1007/s00256-006-0216-z.
10. Xu Y, Li Q, Su P, Shen T, Zhu Y. MDCT and MRI for the diagnosis of complex fractures of the tibial plateau: A case

control study. Exp Ther Med. 2014; 7(1):199-203. doi:10.3892/etm.2013.1380.

11. Gardner MJ, Yacoubian S, Geller D, et al. The incidence of soft tissue injury in operative tibial plateau fractures: a magnetic resonance imaging analysis of 103 patients. J Orthop Trauma. 2005; 19(2):79-84. doi:10.1097/00005131-200502000-00002.
12. Stahl D, Serrano-Riera R, Collin K, Griffing R, Defenbaugh B, Sagi HC. Operatively Treated Meniscal Tears Associated With Tibial Plateau Fractures: A Report on 661 Patients. J Orthop Trauma. 2015; 29(7):322-324. doi:10.1097/BOT.0000000000000290.
13. Lee AK, Cooper SA, Collinge C. Bicondylar Tibial Plateau Fractures: A Critical Analysis Review. JBJS Rev. 2018;6(2). doi: 10.2106/JBJS.RVW.17.00050.
14. Henry P, Wasserstein D, Paterson M, Kreder H, Jenkinson R. Risk factors for reoperation and mortality after the operative treatment of tibial plateau fractures in Ontario, 1996-2009. J Orthop Trauma. 2015; 29(4):182-188. doi:10.1097/BOT.0000000000000237.
15. Jansen H, Frey SP, Doht S, Fehske K, Meffert RH. Medium-term results after complex intra-articular fractures of the tibial plateau. J Orthop Sci. 2013; 18(4):569-577. doi:10.1007/s00776-013-0404-3.
16. Märdian S, Landmann F, Wichlas F, Haas NP, Schaser KD, Schwabe P. Outcome of angular stable locking plate fixation of tibial plateau fractures Midterm results in 101 patients. Indian J Orthop. 2015; 49(6):620-629. doi:10.4103/0019-5413.168755.
17. Ruffolo MR, Gettys FK, Montijo HE, Seymour RB, Karunakar MA. Complications of high-energy bicondylar tibial plateau fractures treated with dual plating through 2 incisions. J Orthop Trauma. 2015; 29(2):85-90. doi:10.1097/BOT.0000000000000203.
18. Barei DP, Nork SE, Mills WJ, Henley MB, Benirschke SK. Complications associated with internal fixation of high-energy bicondylar tibial plateau fractures utilizing a two-incision technique. J Orthop Trauma. 2004; 18(10):649-657. doi:10.1097/00005131-200411000-00001.
19. Gosling T, Schandelmaier P, Muller M, Hankemeier S, Wagner M, Krettek C. Single lateral locked screw plating of bicondylar tibial plateau fractures. Clin Orthop Relat Res. 2005; 439:207-214. doi:10.1097/00003086-200510000-00036.
20. Morris BJ, Unger RZ, Archer KR, Mathis SL, Perdue AM, Obremskey WT. Risk factors of infection after ORIF of bicondylar tibial plateau fractures. J Orthop Trauma. 2013; 27(9):e196-200. doi:10.1097/BOT.0b013e318284704e.
21. Barei DP, Nork SE, Mills WJ, Coles CP, Henley MB, Benirschke SK. Functional outcomes of severe bicondylar tibial plateau fractures treated with dual incisions and medial and lateral plates. J Bone Joint Surg Am. 2006; 88(8):1713-1721. doi:10.2106/JBJS.E.00907.
22. Basques BA, Webb ML, Bohl DD, Golinvaux NS, Grauer JN. Adverse events, length of stay, and readmission after surgery for tibial plateau fractures. J Orthop Trauma. 2015; 29(3):e121-6. doi:10.1097/BOT.0000000000000231.
23. Khatri K, Lakhotia D, Sharma V, Kiran Kumar GN, Sharma G, Farooque K. Functional Evaluation in High Energy (Schatzker Type V and Type VI) Tibial Plateau Fractures Treated by Open Reduction and Internal Fixation. Int Sch Res Notices. 2014; 2014:589538. doi:10.1155/2014/589538.
24. Young MJ, Barrack RL. Complications of internal fixation of tibial plateau fractures. Orthop Rev. 1994; 23(2):149-154.
25. Schatzker J, McBroom R, Bruce D. The tibial plateau fracture. The Toronto experience 1968--1975. Clin Orthop Relat Res. 1979 :(138):94-104.
26. Stark E, Stucken C, Trainer G, Tornetta P. Compartment syndrome in Schatzker type VI plateau fractures and medial condylar fracture-dislocations treated with temporary external fixation. J Orthop Trauma. 2009; 23(7):502-506. doi:10.1097/BOT.0b013e3181a18235.
27. Ziran BH, Becher SJ. Radiographic predictors of compartment syndrome in tibial plateau fractures. J Orthop Trauma. 2013; 27(11):612-615. doi:10.1097/BOT.0b013e31828e25b6.
28. Firoozabadi R, Schneidkraut J, Beingessner D, Dunbar R, Barei D. Hyperextension Varus Bicondylar Tibial Plateau Fracture Pattern: Diagnosis and Treatment Strategies. J Orthop Trauma. 2016; 30(5):e152-7. doi:10.1097/BOT.0000000000000510.
29. Blair JA, Stoops TK, Doarn MC, et al. Infection and Nonunion After Fasciotomy for Compartment Syndrome Associated With Tibia Fractures: A Matched Cohort Comparison. J Orthop Trauma. 2016; 30(7):392-396. doi:10.1097/BOT.0000000000000570.
30. Bible JE, McClure DJ, Mir HR. Analysis of single-incision versus dual-incision fasciotomy for tibial fractures with acute compartment syndrome. J Orthop Trauma. 2013; 27(11):607-611. doi:10.1097/BOT.0b013e318291f284.
31. Liow RY, Birdsall PD, Mucci B, Greiss ME. Spiral computed tomography with two- and three-dimensional reconstruction in the management of tibial plateau fractures. Orthopedics. 1999; 22(10):929-932.
32. Chan PS, Klimkiewicz JJ, Luchetti WT, et al. Impact of CT scan on treatment plan and fracture classification of tibial plateau fractures. J Orthop Trauma. 1997; 11(7):484-489. doi:10.1097/00005131-199710000-00005.
33. Maripuri SN, Rao P, Manoj-Thomas A, Mohanty K. The classification systems for tibial plateau fractures: how reliable are they? Injury. 2008; 39(10):1216-1221. doi:10.1016/j.injury.2008.01.023.
34. Taşkesen A, Demirkale İ, Okkaoğlu MC, Özdemir M, Bilgili MG, Altay M. Intraobserver and interobserver reliability assessment of tibial plateau fracture classification systems. Eklem Hastalik Cerrahisi. 2017; 28(3):177-181. doi:10.5606/ehc.2017.56816.
35. Yang G, Zhai Q, Zhu Y, Sun H, Putnis S, Luo C. The incidence of posterior tibial plateau fracture: an investigation of 525 fractures by using a CT-based classification system. Arch Orthop Trauma Surg. 2013; 133(7):929-934. doi:10.1007/s00402-013-1735-4.
36. Luo CF, Sun H, Zhang B, Zeng BF. Three-column fixation for complex tibial plateau fractures. J Orthop Trauma. 2010; 24(11):683-692. doi:10.1097/BOT.0b013e3181d436f3.
37. Weigel DP, Marsh JL. High-energy fractures of the tibial plateau. Knee function after longer follow-up. J Bone Joint Surg Am. 2002; 84(9):1541-1551. doi:10.2106/00004623-200209000-00006.
38. Volpin G, Dowd GS, Stein H, Bentley G. Degenerative arthritis

after intra-articular fractures of the knee. Long-term results. J Bone Joint Surg Br. 1990; 72(4):634-638. doi:10.1302/0301-620X.72B4.2380219.
39. Honkonen SE. Degenerative arthritis after tibial plateau fractures. J Orthop Trauma. 1995; 9(4):273-277. doi:10.1097/00005131-199509040-00001.
40. Lansinger O, Bergman B, Körner L, Andersson GB. Tibial condylar fractures. A twenty-year follow-up. J Bone Joint Surg Am. 1986; 68(1):13-19.
41. Blokker CP, Rorabeck CH, Bourne RB. Tibial plateau fractures. An analysis of the results of treatment in 60 patients. Clin Orthop Relat Res. 1984 ;(182):193-199.
42. Honkonen SE. Indications for surgical treatment of tibial condyle fractures. Clin Orthop Relat Res. 1994 ;(302):199-205.
43. Marsh JL, Buckwalter J, Gelberman R, et al. Articular fractures: does an anatomic reduction really change the result? J Bone Joint Surg Am. 2002; 84(7):1259-1271.
44. Moore TM, Patzakis MJ, Harvey JP. Tibial plateau fractures: definition, demographics, treatment rationale, and long-term results of closed traction management or operative reduction. J Orthop Trauma. 1987; 1(2):97-119.
45. Kettelkamp DB, Hillberry BM, Murrish DE, Heck DA. Degenerative arthritis of the knee secondary to fracture malunion. Clin Orthop Relat Res. 1988 ;(234):159-169.
46. Lee AK, Cooper SA, Collinge C. Bicondylar Tibial Plateau Fractures. JBJS Rev. 2018; 6(2):e4-e4. doi:10.2106/JBJS.RVW.17.00050.
47. Egol KA, Tejwani NC, Capla EL, Wolinsky PL, Koval KJ. Staged management of high-energy proximal tibia fractures (OTA types 41): the results of a prospective, standardized protocol. J Orthop Trauma. 2005; 19(7):448-455; discussion 456. doi:10.1097/01.bot.0000171881.11205.80.
48. Unno F, Lefaivre KA, Osterhoff G, et al. Is Early Definitive Fixation of Bicondylar Tibial Plateau Fractures Safe? An Observational Cohort Study. J Orthop Trauma. 2017; 31(3):151-157. doi:10.1097/BOT.0000000000000779.
49. Stenquist D, Yeung CM, Guild T, et al. Judicious Early Primary ORIF for Closed AO/OTA 41C (Schatzker VI) Bicondylar Tibial Plateau Fractures Is Not Associated with Increased Risk of Deep Infection or Reoperation.; 2021.
50. Virkus WW, Caballero J, Kempton LB, Cavallero M, Rosales R, Gaski GE. Costs and Complications of Single-Stage Fixation versus 2-Stage Treatment of Select Bicondylar Tibial Plateau Fractures. J Orthop Trauma. 2018; 32(7):327-332. doi:10.1097/BOT.0000000000001167.
51. Zura RD, Adams SB, Jeray KJ, et al. Timing of definitive fixation of severe tibial plateau fractures with compartment syndrome does not have an effect on the rate of infection. J Trauma. 2010; 69(6):1523-1526. doi:10.1097/TA.0b013e3181d40403.
52. Parekh AA, Smith WR, Silva S, et al. Treatment of distal femur and proximal tibia fractures with external fixation followed by planned conversion to internal fixation. J Trauma. 2008; 64(3):736-739. doi:10.1097/TA.0b013e31804d492b.
53. Perdue A, Greenberg SE, Sathiyakumar V, et al. Staged Columnar Fixation of Bicondylar Tibial Plateaus: A Cheaper Alternative to External Fixation. J Surg Orthop Adv. 2016; 25(1):13-17.
54. Prat-Fabregat S, Camacho-Carrasco P. Treatment strategy for tibial plateau fractures: an update. EFORT Open Rev. 2016; 1(5):225-232. doi:10.1302/2058-5241.1.000031.
55. Ricci WM, Rudzki JR, Borrelli J. Treatment of complex proximal tibia fractures with the less invasive skeletal stabilization system. J Orthop Trauma. 2004; 18(8):521-527. doi:10.1097/00005131-200409000-00007.
56. Weaver MJ, Harris MB, Strom AC, et al. Fracture pattern and fixation type related to loss of reduction in bicondylar tibial plateau fractures. Injury. 2012; 43(6):864-869. doi:10.1016/j.injury.2011.10.035.
57. Barei DP, O'Mara TJ, Taitsman LA, Dunbar RP, Nork SE. Frequency and fracture morphology of the posteromedial fragment in bicondylar tibial plateau fracture patterns. J Orthop Trauma. 2008; 22(3):176-182. doi:10.1097/BOT.0b013e318169ef08.
58. Chang SM, Wang X, Zhou JQ, Huang YG, Zhu XZ. Posterior coronal plating of bicondylar tibial plateau fractures through posteromedial and anterolateral approaches in a healthy floating supine position. Orthopedics. 2012; 35(7):583-588. doi:10.3928/01477447-20120621-03.
59. Carlson DA. Posterior bicondylar tibial plateau fractures. J Orthop Trauma. 2005; 19(2):73-78. doi:10.1097/00005131-200502000-00001.
60. Chang SM, Hu SJ, Zhang YQ, et al. A surgical protocol for bicondylar four-quadrant tibial plateau fractures. Int Orthop. 2014; 38(12):2559-2564. doi:10.1007/s00264-014-2487-7.
61. He X, Ye P, Hu Y, et al. A posterior inverted L-shaped approach for the treatment of posterior bicondylar tibial plateau fractures. Arch Orthop Trauma Surg. 2013; 133(1):23-28. doi:10.1007/s00402-012-1632-2.
62. Lin KC, Tarng YW, Lin GY, Yang SW, Hsu CJ, Renn JH. Prone and direct posterior approach for management of posterior column tibial plateau fractures. Orthop Traumatol Surg Res. 2015; 101(4):477-482. doi:10.1016/j.otsr.2014.12.021.
63. Weil YA, Gardner MJ, Boraiah S, Helfet DL, Lorich DG. Posteromedial supine approach for reduction and fixation of medial and bicondylar tibial plateau fractures. J Orthop Trauma. 22(5):357-362. doi:10.1097/BOT.0b013e318168c72e.
64. Kandemir U, Maclean J. Surgical approaches for tibial plateau fractures. J Knee Surg. 2014; 27(1):21-29. doi:10.1055/s-0033-1363519.
65. Galla M, Lobenhoffer P. [The direct, dorsal approach to the treatment of unstable tibial posteromedial fracture-dislocations]. Unfallchirurg. 2003; 106(3):241-247. doi:10.1007/s00113-002-0554-9.
66. Fakler JKM, Ryzewicz M, Hartshorn C, Morgan SJ, Stahel PF, Smith WR. Optimizing the management of Moore type I postero-medial split fracture dislocations of the tibial head: description of the Lobenhoffer approach. J Orthop Trauma. 2007; 21(5):330-336. doi:10.1097/BOT.0b013e318055603c.
67. Solomon LB, Stevenson AW, Baird RP v, Pohl AP. Posterolateral transfibular approach to tibial plateau fractures: technique, results, and rationale. J Orthop Trauma. 2010; 24(8):505-514. doi:10.1097/BOT.0b013e3181ccba4b.
68. Solomon LB, Stevenson AW, Lee YC, Baird RP v, Howie DW. Posterolateral and anterolateral approaches to unicondylar posterolateral tibial plateau fractures: a comparative study.

Injury. 2013; 44(11):1561-1568. doi:10.1016/j.injury.2013.04.024.
69. Schütz M, Kääb MJ, Haas N. Stabilization of proximal tibial fractures with the LIS-System: early clinical experience in Berlin. Injury. 2003; 34 Suppl 1:A30-5. doi:10.1016/s0020-1383(03)00255-9.
70. Stannard JP, Wilson TC, Volgas DA, Alonso JE. Fracture stabilization of proximal tibial fractures with the proximal tibial LISS: early experience in Birmingham, Alabama (USA). Injury. 2003; 34 Suppl 1:A36-42. doi:10.1016/s0020-1383(03)00256-0.
71. Cole PA, Zlowodzki M, Kregor PJ. Less Invasive Stabilization System (LISS) for fractures of the proximal tibia: indications, surgical technique and preliminary results of the UMC Clinical Trial. Injury. 2003; 34 Suppl 1:A16-29. doi:10.1016/s0020-1383(03)00254-7.
72. Mills WJ, Nork SE. Open reduction and internal fixation of high-energy tibial plateau fractures. Orthop Clin North Am. 2002; 33(1):177-198, ix. doi:10.1016/s0030-5898(03)00079-8.
73. Horwitz DS, Bachus KN, Craig MA, Peters CL. A biomechanical analysis of internal fixation of complex tibial plateau fractures. J Orthop Trauma. 1999;13(8):545-549. doi:10.1097/00005131-199911000-00005.
74. Mueller KL, Karunakar MA, Frankenburg EP, Scott DS. Bicondylar tibial plateau fractures: a biomechanical study. Clin Orthop Relat Res. 2003 ;(412):189-195. doi:10.1097/01.blo.0000071754.41516.e9.
75. Gösling T, Schandelmaier P, Marti A, Hufner T, Partenheimer A, Krettek C. Less invasive stabilization of complex tibial plateau fractures: a biomechanical evaluation of a unilateral locked screw plate and double plating. J Orthop Trauma. 2004; 18(8):546-551. doi:10.1097/00005131-200409000-00011.
76. Higgins TF, Klatt J, Bachus KN. Biomechanical analysis of bicondylar tibial plateau fixation: how does lateral locking plate fixation compare to dual plate fixation? J Orthop Trauma. 2007; 21(5):301-306. doi:10.1097/BOT.0b013e3180500359.
77. Yoo BJ, Beingessner DM, Barei DP. Stabilization of the posteromedial fragment in bicondylar tibial plateau fractures: a mechanical comparison of locking and nonlocking single and dual plating methods. J Trauma. 2010; 69(1):148-155. doi:10.1097/TA.0b013e3181e17060.
78. Lee MH, Hsu CJ, Lin KC, Renn JH. Comparison of outcome of unilateral locking plate and dual plating in the treatment of bicondylar tibial plateau fractures. J Orthop Surg Res. 2014; 9:62. doi:10.1186/s13018-014-0062-y.
79. Neogi DS, Trikha V, Mishra KK, Bandekar SM, Yadav CS. Comparative study of single lateral locked plating versus double plating in type C bicondylar tibial plateau fractures. Indian J Orthop. 2015; 49(2):193-198. doi:10.4103/0019-5413.152478.
80. Chang H, Zhu Y, Zheng Z, et al. Meta-analysis shows that highly comminuted bicondylar tibial plateau fractures treated by single lateral locking plate give similar outcomes as dual plate fixation. Int Orthop. 2016; 40(10):2129-2141. doi:10.1007/s00264-016-3157-8.
81. Hall JA, Beuerlein MJ, McKee MD, Canadian Orthopaedic Trauma Society. Open reduction and internal fixation compared with circular fixator application for bicondylar tibial plateau fractures. Surgical technique. J Bone Joint Surg Am. 2009; 91 Suppl 2 Pt 1:74-88. doi:10.2106/JBJS.G.01165.
82. Ariffin HM, Mahdi NM, Rhani SA, Baharudin A, Shukur MH. Modified hybrid fixator for high-energy Schatzker V and VI tibial plateau fractures. Strategies Trauma Limb Reconstr. 2011; 6(1):21-26. doi:10.1007/s11751-011-0105-4.
83. Babis GC, Evangelopoulos DS, Kontovazenitis P, Nikolopoulos K, Soucacos PN. High energy tibial plateau fractures treated with hybrid external fixation. J Orthop Surg Res. 2011; 6:35. doi:10.1186/1749-799X-6-35.
84. Ali AM. Outcomes of open bicondylar tibial plateau fractures treated with Ilizarov external fixator with or without minimal internal fixation. Eur J Orthop Surg Traumatol. 2013; 23(3):349-355. doi:10.1007/s00590-012-0989-9.
85. Dendrinos GK, Kontos S, Katsenis D, Dalas A. Treatment of high-energy tibial plateau fractures by the Ilizarov circular fixator. J Bone Joint Surg Br. 1996; 78(5):710-717.
86. Keightley AJ, Nawaz SZ, Jacob JT, Unnithan A, Elliott DS, Khaleel A. Ilizarov management of Schatzker IV to VI fractures of the tibial plateau: 105 fractures at a mean follow-up of 7.8 years. Bone Joint J. 2015; 97-B(12):1693-1697. doi:10.1302/0301-620X.97B12.34635.
87. Barei DP, Nork SE, Mills WJ, Henley MB, Benirschke SK. Complications associated with internal fixation of high-energy bicondylar tibial plateau fractures utilizing a two-incision technique. J Orthop Trauma. 18(10):649-657. doi:10.1097/00005131-200411000-00001.
88. van Dreumel RLM, van Wunnik BPW, Janssen L, Simons PCG, Janzing HMJ. Mid- to long-term functional outcome after open reduction and internal fixation of tibial plateau fractures. Injury. 2015; 46(8):1608-1612. doi:10.1016/j.injury.2015.05.035.
89. Stevens DG, Beharry R, McKee MD, Waddell JP, Schemitsch EH. The Long-Term Functional Outcome of Operatively Treated Tibial Plateau Fractures. J Orthop Trauma. 2001; 15(5):312-20. doi: 10.1097/00005131-200106000-00002.
90. Warschawski Y, Elbaz A, Segal G, et al. Gait characteristics and quality of life perception of patients following tibial plateau fracture. Arch Orthop Trauma Surg. 2015; 135(11):1541-1546. doi:10.1007/s00402-015-2325-4.
91. Timmers TK, van der Ven DJC, de Vries LS, van Olden GDJ. Functional outcome after tibial plateau fracture osteosynthesis: a mean follow-up of 6 years. Knee. 2014; 21(6):1210-1215. doi:10.1016/j.knee.2014.09.011.
92. Marti RK, Kerkhoffs GMMJ, Rademakers M v. Correction of lateral tibial plateau depression and valgus malunion of the proximal tibia. Oper Orthop Traumatol. 2007; 19(1):101-113. doi:10.1007/s00064-007-1197-3.
93. Manidakis N, Dosani A, Dimitriou R, Stengel D, Matthews S, Giannoudis P. Tibial plateau fractures: functional outcome and incidence of osteoarthritis in 125 cases. Int Orthop. 2010; 34(4):565-570. doi:10.1007/s00264-009-0790-5.
94. Mattiassich G, Foltin E, Scheurecker G, Schneiderbauer A, Kröpfl A, Fischmeister M. Radiographic and clinical results after surgically treated tibial plateau fractures at three and twenty two years postsurgery. Int Orthop. 2014; 38(3):587-594. doi:10.1007/s00264-013-2174-0.

95. Stenquist DS, Yeung CM, Guild T, Weaver MJ, Harris MB, von Keudell AG. Is It Safe to Prep the External Fixator In Situ During Staged ORIF of Bicondylar Tibial Plateau Fractures? A Retrospective Comparative Cohort Study. J Orthop Trauma. 2022 Aug 1; 36(8):382-387. doi:10.1097/BOT.0000000000002334.
96. O'Toole RV, Joshi M, Carlini AR, et al. Effect of intrawound vancomycin powder in operatively treated high-risk tibia fractures: a randomized clinical trial. JAMA Surg. 2021; 156(5):e207259. doi:10.1001/jamasurg.2020.7259.
97. The FLOW Investigators. A Trial of Wound Irrigation in the Initial Management of Open Fracture Wounds. New England Journal of Medicine. 2015; 373(27):2629-2641. doi:10.1056/NEJMoa1508502.
98. Shen S, Wang P, Li X, Han X, Tan H. Pre-operative simulation using a three-dimensional printing model for surgical treatment of old and complex tibial plateau fractures. Sci Rep. 2020; 10(1):6044. doi:10.1038/s41598-020-63219-w.
99. Mabrey JD, Reinig KD, Cannon WD. Virtual reality in orthopaedics: is it a reality? Clin Orthop Relat Res. 2010; 468(10):2586-2591. doi:10.1007/s11999-010-1426-1.
100. Lohre R, Bois AJ, Pollock JW, et al. Effectiveness of Immersive Virtual Reality on Orthopedic Surgical Skills and Knowledge Acquisition among Senior Surgical Residents. JAMA Netw Open. 2020; 3(12):e2031217. doi:10.1001/jamanetworkopen.2020.31217.
101. Wixted CM, Peterson JR, Kadakia RJ, Adams SB. Three-dimensional Printing in Orthopaedic Surgery: Current Applications and Future Developments. JAAOS: Global Research and Reviews. 2021; 5(4):e20.00230-11. doi:10.5435/JAAOSGlobal-D-20-00230.
102. Lou Y, Cai L, Wang C, et al. Comparison of traditional surgery and surgery assisted by three dimensional printing technology in the treatment of tibial plateau fractures. Int Orthop. 2017; 41(9):1875-1880. doi:10.1007/s00264-017-3445-y.
103. Giannetti S, Bizzotto N, Stancati A, Santucci A. Minimally invasive fixation in tibial plateau fractures using an pre-operative and intra-operative real size 3D printing. Injury. 2017; 48(3):784-788. doi:10.1016/j.injury.2016.11.015.