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The surgical approach for osteosynthesis of metaepiphyseal fractures of the distal tibia

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Abstract

Introduction The optimal surgical approach is essential for osteosynthesis of intra-articular fractures of the distal tibial metaphysis (pilon fractures). None of the existing approaches provides complete visualization of the articular surface, increasing the risk of complications and inadequate reduction.

The **objective** was to optimize the choice of surgical approach in preoperative planning of internal osteosynthesis of intra-articular fractures of the distal metaepiphysis of the tibia (pilon) based on 3D prototyping and standardized marking of the articular surface.

Material and methods An algorithm developed was based on a full-size 3D prototype and CT data. The articular surface of the tibia was divided into nine standard zones. The surgical approach was selected depending on the location of the key fragment (occupying > 2/3 of the zone) or the fracture line exit point. The method was used in 12 patients with AO/OTA 43-C pilon fractures. Surgical time, blood loss, the quality of postoperative fracture reduction categorized according to the Burwell-Charnley criteria, functional outcomes measured with AOFAS and VAS FA grading scales, and radiographic union determined with the mRUST scale were assessed at six months.

Results and discussion The mean operating time was (65.08 ± 7.03) min, blood loss was (119.3 ± 18.51) ml. The wounds healed by primary intention without infectious complications. The quality of reduction was anatomical in eight patients and acceptable in four patients. The mean AOFAS (78.67 ± 8.68) and VAS FA (41.08 ± 5.05) scores indicated good functional recovery. The mean mRUST score (13.5 ± 1.43) suggested complete consolidation. The method objectified the surgical approach avoiding subjectivity and allowed for personalized intervention by combining approaches for optimal visualization of all fragments, including hard-to-reach ones (e.g., Tillaux-Chaput fragment).

Conclusion The method integrating 3D planning and a standardized coordinate system improves reposition accuracy, reduces morbidity, and improves functional outcomes in patients with complex pilon fractures.

Keywords: intra-articular fracture, distal tibia metaepiphysis, pilon fracture, 3D-model, surgical approach, osteosynthesis, selection algorithm

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INTRODUCTION

Osteosynthesis of metaepiphyseal fractures of the distal tibia is a procedure that requires high surgical skill and clinical equipment. Surgical approach, surgical technique, timing of the procedure and postoperative rehabilitation are essential for successful outcome. Pilon fractures often result from high-energy trauma and are accompanied by massive destruction of the articular surface of the tibia and severe damage to the soft tissue. Careful treatment of soft tissues during the surgical approach is essential for healing. A variety of surgical approaches to the distal tibia have been reported to include medial, anteromedial, anterolateral, lateral, posterolateral and posteromedial approaches. Each of the approaches allows for visualization of a portion of the pilon to reduce the corresponding fragment of the articular surface [1]. The concept of osteosynthetic stability forms the basis of the column theory. According to the theory, the distal tibia is divided into three columns (lateral, medial, and posterior) with each requiring separate fixation. This often necessitates a combination of different approaches. The main problem is that increasing their number during surgical intervention allows for greater stability of the construct increasing the risk of complications (infection, soft tissue necrosis, non-union), which poses a difficult task for the surgeon with the optimal balance to be found between reliable fixation and minimal surgical trauma [2]. Mayorov et al. developed the concept of "preoperative 360° visualization", which is based on a comprehensive analysis of radiographic and CT findings [3].The concept allows for a detailed study of the individual characteristics of the fracture architecture, precise visualization of all components of the injury, determination of the most appropriate surgical approaches, selection and optimal placement of implants. The approach enables thorough preoperative planning improving the precision of the surgical intervention. However, the study does not provide a clear step-by-step algorithm for selecting a surgical approach. Fracture morphology would be a key point in the approach to be selected. Cole et al. examined the distribution of fracture lines and the location of major bone fragments in 38 cases of comminuted AO/OTA 43-C3 fractures of the distal metaphysis of the tibial tuberosity and concluded that a good understanding of fracture morphology should guide the choice of surgical approach [4]. However, this study did not provide a detailed explanation of how to choose a surgical approach based on the specific distribution of fracture lines and bone fragments.

Kleinetz et al. explored the effectiveness of four surgical approaches to the distal tibia (anteromedial, anterolateral, posteromedial, and posterolateral) and the effect of instrumental distraction on the visualization of the articular surface using cadaveric material [5]. In the study, the authors used a standardized technique for marking the articular surface to objectively assess the accessibility of various anatomical zones through surgical approaches: the articular surface was divided into segments to enable a quantitative assessment of which part is accessible and corresponds to each of them.

The markings were performed using a coordinate system based on anatomical landmarks (e.g., the anterior and posterior edges of the articular surface). A unique identifier was assigned for each zone to facilitate comparison of the accessibility of areas between different surgical approaches. For each approach, the percentage of the articular surface visible was assessed with and without distraction. Visible zones were marked, and the percentage of accessible surface was calculated using specialized software. The researchers concluded that most approaches provided extremely limited visibility without distraction, with maximum visibility achieved with the posterolateral approach (30 %) and minimum visibility seen with the anteromedial approach. With distraction, visibility of the articular surface increased significantly, with the anterolateral (up to 72 %) and anteromedial (up to 63 %) approaches, in particular. However, neither approach provided complete visualization of the articular surface.

Three-dimensional technologies used for planning of surgical treatment of patients with fractures of the distal metaepiphysis of the tibial tuberosity are reported by Parshkov et al. [6]. Compared with traditional methods, the use of 3D technologies for planning osteosynthesis of pilon fractures, including the choice of surgical approach, allowed us to achieve a significant reduction in surgical time, in intraoperative blood loss and in radiation exposure. The quality of bone reduction and functional treatment outcomes were significantly better in the 3D group.

However, analysis of the outcomes revealed some errors and complications, which can be divided into three groups:

1 — Three-dimensional model preparation and printing errors. Initially, there were issues with CT data segmentation (inclusion of artifacts, missing small fragments), printing defects due to low-quality filament, and incorrect printer calibration. These were resolved by manually correcting the STL files and using higher-quality materials.

2 — Errors in planning of a surgical approach. An extended incision was required in 4 % of cases in the 3D group and in 7 % of the controls.

3 — Postoperative complications. Wound dehiscence occurred after suture removal in one patient of the 3D group and in two controls. In all cases, the dehiscence width did not exceed 3 mm and its length did not exceed 2 cm. Sterile skin strips were used for treatment; re-suturing was not required. No deep suppuration was observed in either group.

While clear and effective methods exist to prevent complications of the first group (errors in preparing and printing 3D models), preventing complications of the second and third groups requires optimizing surgical approach(es) that can be difficult to identify. Therefore, there is no universal surgical approach. An optimal algorithm to be employed for surgical approach requires a compromise between visualization and the risk of complications considering the condition of the soft tissues.

The **objective** was to optimize the choice of a surgical approach in preoperative planning of internal osteosynthesis of intra-articular fractures of the distal metaepiphysis of the tibia (pilon) based on 3D prototyping and standardized marking of the articular surface.

MATERIAL AND METHODS

Description of the method

A 3D prototype was produced as part of preoperative planning using computed tomography (CT) and DICOM files that were converted to STL format and printed on a 3D printer. Markings were made on the articular surface using the results of the cadaveric study reported by Kleinertz et al. [5] connecting the extreme anterior point and the extreme posterior point on the distal aspect of the tibia adjacent to the medial malleolus, and the segment was considered as the inner side of the square. The posterior, lateral, and anterior sides were completed accordingly. The resulting large square was divided into nine equal internal squares, smaller in size: anteromedial, anterocentral, anterolateral, midmedial, midcentral, midlateral, posteromedial, posterior central and posterolateral (Fig. 1), corresponding to nine zones located on the articular surface.

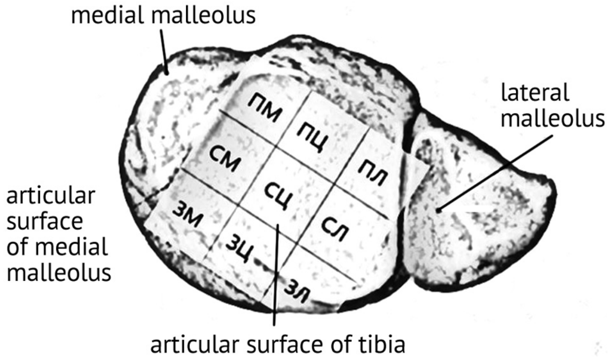

Fig. 1 Marking of the articular surface of the pilon included anteromedial (AM), anterocentral (AC), anterolateral (AL), mid-medial (MM), mid-central (MC), mid-lateral (ML), posteromedial (PM), posterior central (PC), posterolateral (PL) aspects

The largest fragment was identified on the articular surface of the 3D prototype (hereinafter referred to as the key fragment) and reduced first with the coordinates determined on the markings. If more than two-thirds of the fragment corresponded to a specific square, the coordinates were assigned to that square. If two fragments of the same size were present, two approaches were selected in the same manner. If a fragment was located within two or more squares, the coordinates of the fracture line exiting onto the anterior or posterior surface were determined, rather than the fragment itself. The method proved to be inappropriate in the absence of fragments covering more than two-thirds of the fragments with treatment using a compression-distraction device.

Depending on the location of the fragment and the exit point of the fracture line in a certain square, an approach was chosen from the classical approaches of AO described:

Square	Approach
anteromedial	anteromedial
anterocentral	anterolateral
anterolateral	Передне-латеральный
mid-medial	Задне-медиальный
mid-central	anterolateral, задне-латеральный
mid-lateral	anterolateral, задне-латеральный
posteromedial	posteromedial
posterior central	posterolateral
posterolateral	posterolateral

anteromedial (AM), anterocentral (AC), anterolateral (AL), mid-medial (MM), mid-central (MC), mid-lateral (ML), posteromedial (PM), posterior central (PC), posterolateral (PL) aspects

The study was conducted between January 1, 2024 and December 31, 2024 at the Trauma Department of the University Clinic of the N.A. Semashko Scientific and Educational Institute of Clinical Medicine of the Russian University of Medicine. The study was approved by the Ethics Committee of the Russian University of Medicine (protocol No. 12-23 dtd December 15, 2023).

The study included 12 patients with intra-articular fractures of the distal metaepiphysis of the tibia (10 patients with type 43C2 and two patients with type 43C3). The fractures were repaired with an external fixator upon admission. With the frame applied CT findings were used to create a 3D model to determine the surgical approach according to the specified technique. Internal osteosynthesis was performed with the edema settled. The period between the dates of hospitalization and surgery was (8.2 ± 3.2) days. Duration of the intervention and volume of blood loss were assessed intraoperatively using the gravimetric method. The surgery time was (65.08 ± 7.03) minutes, blood loss was (119.3 ± 18.51) ml.

The postoperative wounds healed on time, no purulent-inflammatory complications were registered. The effectiveness of reposition was assessed according to the Burwell-Charnley criteria [7]: the result was rated as anatomical (n = 8) and fair (n = 4). No poor outcomes were observed. Functional results were assessed at six months using the AOFAS AHS scale [8] and the VAS FA visual analogue scale [9]. AOFAS scored (78.67 ± 8.68) and VAS FA scored (41.08 ± 5.05) that suggested a good functional recovery of the ankle joint and a high degree of patient satisfaction. The fracture consolidation index according to the modified mRUST scale [10] measured (13.5 ± 1.43) suggesting complete fracture consolidation.

Clinical instance

A 52-year-old patient was diagnosed with a closed, multi-comminuted, intra-articular fracture of the distal metaphysis of the left tibia with bone displacement. The trauma resulted from a fall from a four-meter height onto straight legs. Six hours after admission, the left tibia and the foot were fixed with an external fixator. Then a CT scan was produced to allow a full-size 3D prototype to be fabricated (Fig. 2). The articular surface of the prototype was marked (Fig. 3), and the key fragments were identified on posterolateral and anterolateral aspects and the fracture exit points determined in the anterocentral and posteromedial quadrants.

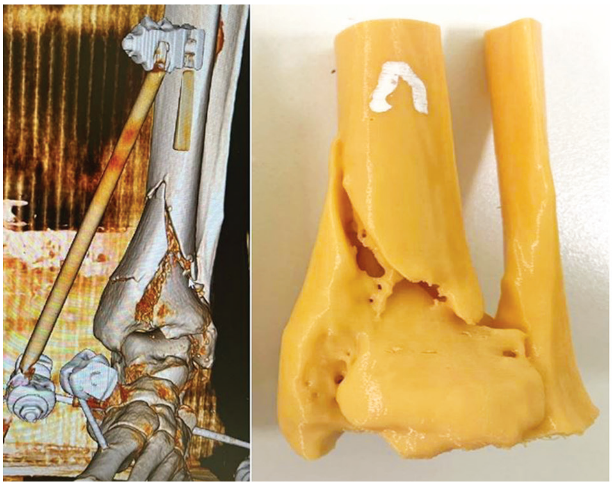

Fig. 2 3D reconstruction of computed tomography data of the fracture and the 3D prototype

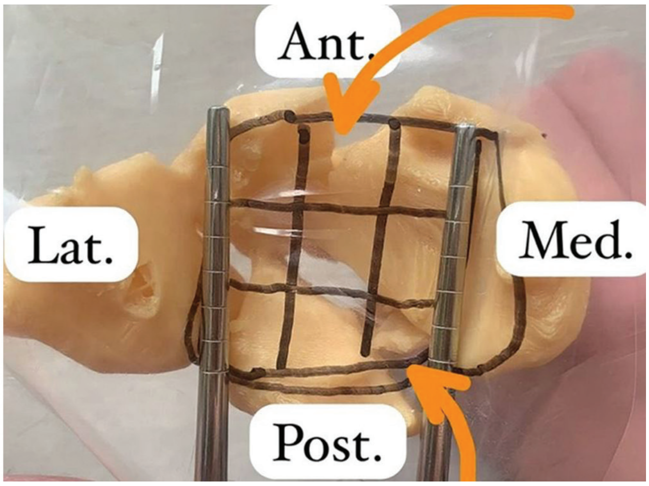

Fig. 3 Marking the articular surface of the 3D prototype indicating the exit points of the fracture lines on the anterior and posterior aspects of the tibia

Posteromedial and anterolateral surgical approaches were used based on the data obtained. Osteosynthesis was performed using these approaches and an anterolateral plate and a 1/3 tubular plate were placed posteriorly (Fig. 4). The posteromedial approach allowed for complete visualization of the posterior aspect of the broken tibia, the bone reduced ad occulus, and the 1/3 premodeled tubular plate placed using a 3D prototype. The patient was then turned supine, and an anterolateral approach was performed. The metadiaphyseal component of the fracture was fixed with an anterolateral premodeled L-plate, and the anterolateral fragment (Chaput) was fixed with a screw. The approach allowed for visualization of the anterior edge of the fibular notch for precise reduction of the Chaput fragment.

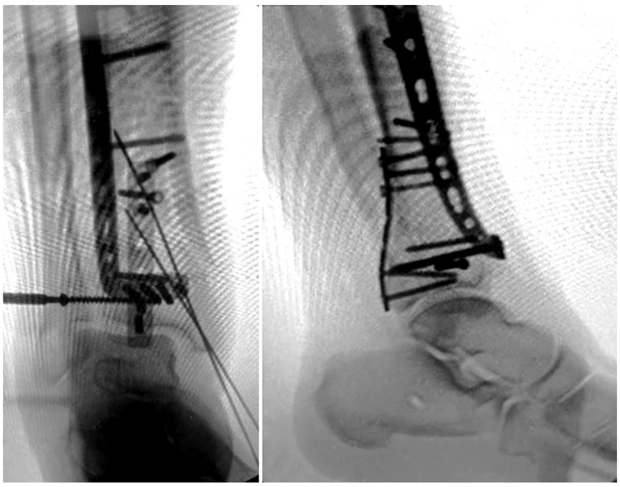

Fig. 4 AP and lateral intraoperative views

The postoperative period was uneventful, and the wounds healed by primary intention. The patient was encouraged to exercise the operated ankle joint for eight weeks. The treatment outcome was rated as satisfactory at a six-month follow-up examination. The AOFAS AHS scored 82 and the VAS-FA scored 41 suggesting excellent results. Radiographs (Fig. 5) showed a mRUST score of 13 being consistent with a fracture in the consolidation stage. No signs of fixator migration or secondary displacement were detected.

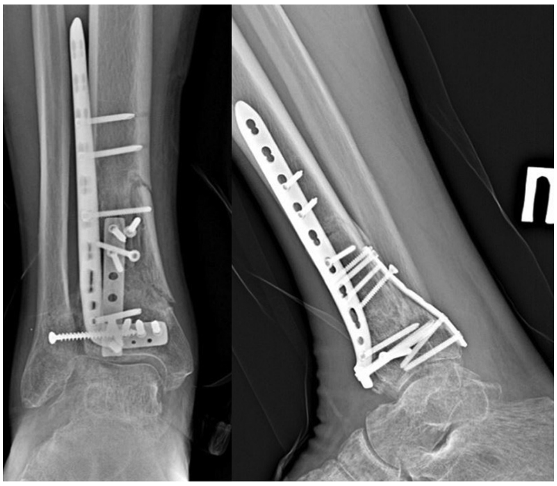

Fig. 5 Radiographs at a 6-month follow-up

DISCUSSION

Understanding the precise morphological characteristics of a distal tibial metaphysis fracture is a key to successful treatment. The classical surgical approaches offered by T. Ruedi and M. Allgower for repair of pilon fractures are widely used today. However, the morphological variations of these fractures are extremely diverse, and mechanically copying these principles and surgical approaches can lead to unexpected outcomes and treatment failure in some severe cases.

Assal et al. recommend choosing a surgical approach based on the biomechanics of the injury in order to place a support plate on the compression side [11]. Experts from the AO group, Buckley and Sands, suggest taking into account the size of the anterolateral fragment when choosing an approach [12]. An anteromedial approach can be recommended for larger fractures and fractures with the proximity to the medial malleolus. An anterolateral approach is practical for smaller anterolateral fragments and a more lateral location of the fracture plane. The disadvantage of this method includes the lack of definition of the anterolateral fragment, clear criteria for a "larger" or "smaller" size, and "proximity of the fracture line to the medial malleolus."

Liu et al. reported a meta-analysis of 19 articles (733 patients) on surgical approaches and treatment outcomes in open reduction and internal fixation of pilon fractures and found out 30 % of operations were performed using the anterolateral approach. The average complication rate was 16 %, the lowest rate was observed with the medial (11.7 %) and anterior (11.8 %) surgical approaches, the highest rate of adverse events seen with the posterolateral (23 %) and anteromedial (22.8 %) approaches. The most severe complications were recorded with the anterolateral approach (12 cases). The most common complications included wound dehiscence (21 %), delayed union or nonunion (19 %) and soft tissue infection (17 %). The difference in complication rates could be associated with the surgical approach, the fracture type or other factors including surgical technique, operative time, use of antibiotics. There was no comparison between different surgical approaches [13]. Babovnikov et al. reported the use of an arcuate postero-internal approach and extended incision to the anterior aspect if needed in case of fragmentation of the posterior and medial portions of the tibial metaepiphysis [14]. The approach could ensure good visual control of the entire articular surface. An anterior approach could be used along the medial edge of the tendon of the tibialis anterior muscle with impaired anterior and central parts of the articular surface of the metaepiphysis with an arcuate continuation to the lateral aspect along the anterior articular surface. This study, systematizing extensive clinical experience in the treatment of patients with intra-articular fractures of the distal tibial metaepiphysis, had limitations. The choice between the only two approaches reduces possibilities of visualization and fixation of the bone fragments. Neither approach can provide a complete overview of the anterolateral fragments (Chaput), which may worsen the accuracy of reposition and long-term results. In addition, the postero-medial approach can be associated with a risk of injury to the neurovascular bundle.

Urrutia et al. reported a comprehensive cadaveric analysis comparing eight distinct surgical approaches to tibial pilon fractures and found that the anteromedial approach yielded the largest exposed area (18.36 cm^2), whereas the anterolateral approach provided the greatest exposed segment (72°). The posteromedial approach proved most effective for exposing the Volkmann fragment, and the anterolateral approach was optimal for accessing the Tillaux – Chaput fragment [15].

Puha et al. offered CT scans to be used for assessment of the articular surface of the tibia with external fixator in place. The authors distinguished medial, central, anterior, and lateral fragments; a medial approach was chosen for fixation of the medial and central fragments, an anterior approach to be used for fractures with predominantly anterior fragments, and an anterolateral approach for fractures with a large lateral component or for simultaneous fixation of the fibula [16].

Mironov et al. suggested using Tang's four-column classification when choosing a surgical approach with the anterior-medial approach being practical for severe injury to the medial column; the anterolateral approach to be employed for injuries to the lateral column; and the posterior approach to be used for damage of the posterior column [17]. However, no mention of the method was there with regard to simultaneous injury to several columns, and the approach was not specified for cases of posterior column damage.

Cole et al. explored distribution of fracture lines and the position of the main fragments in 38 patients with comminuted intra-articular fractures of the distal metaepiphysis of the tibial femur using CT scans and noted three major fragments in the anterolateral, medial, and posterolateral zones. The authors emphasized that understanding of the fracture morphology facilitated a rational choice of surgical approach [4]. No specific algorithm was offered for approach selection. Many authors reporting treatment strategies for the fractures would recommend the use of CT data when choosing an approach [18-20].

Zhao et al. suggested that a CT-based surgical approach would allow for precise restoration of the articular surface and stable fixation of the fracture to ensure good functional outcomes and reduced complication rate. A posteromedial approach can be used in the presence of large posterior fragments extending into the tarsal canal or medial malleolus, while the anterior tibial femur and fibular fractures can be visualized through an anterolateral approach. A posterolateral approach can be used to reduce the posterior fragment of the tibia and lateral malleolus in case of small posterior malleolar fragments without extension into the tarsal canal, and the anterior fragments can be visualized through an anteromedial approach with correction of the incision position depending on the location of the central impression fragment [21]. An advantage of the method is associated with use of CT findings. However, the authors of this publication focused on the posterior portions of the ankle joint, preventing the approach from being universal across the entire range of morphological variants of pilon fractures.

Unlike previous studies, the method offered an objective quantification of the location of key fragments using standardized markings of the articular surface. This eliminates subjectivity in the approach selection and allows for precise determination of which fragment requires primary reduction. This method allows for a combination of classic approaches depending on a specific fracture morphology, ensuring better visualization of all fragments, including the anterolateral (Chaput) aspects to reduce the risk of inadequate reduction. The method can address injuries to multiple columns suggesting specific approaches for each case, including posterior fragments (e.g., posterolateral or posteromedial approaches). The method is based on 3D prototyping to allow precise fracture modeling and determination of optimal approaches, reducing the risk of soft tissue necrosis, optimizing fragment visualization, reducing the incidence of infectious complications and wound dehiscence.

CONCLUSION

The method developed is a synthesis of modern 3D planning technologies, standardized topographic analysis, and a personalized approach. Its implementation in clinical practice The modality can optimize the choice of surgical approach for osteosynthesis of pilon fractures, improving the reduction, stability of fixation and providing a safe procedure. The approach facilitates improved surgical treatment of patients with complex intra-articular fractures of the distal tibial metaphysis.

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