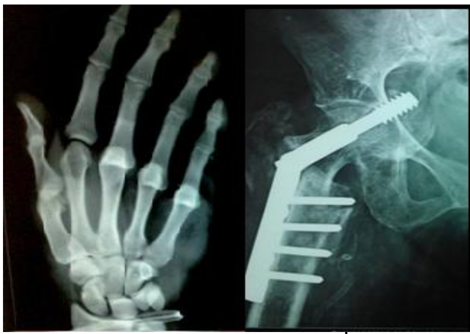

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Role of 3D CT in classification and surgical planning of complex intra-articular fractures: A prospective observational study

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Abstract
Background: Complex intra-articular fractures are challenging to classify and plan for using plain radiographs. Two-dimensional CT (2D CT) adds detail, but may not fully capture fracture geometry. Three-dimensional CT (3D CT) can improve visualization and influence surgical decision-making.
Methods: Prospective observational study of 60 patients with complex intra-articular fractures (tibial plateau n = 32; distal radius intra-articular n = 18; calcaneus intra-articular n = 10). Each case was evaluated using plain radiographs, 2D CT, and 3D CT reconstructions by three independent orthopaedic observers. We assessed interobserver reliability (kappa), reclassification after 3D CT, changes in surgical plan, and concordance with intraoperative findings.
Results: Interobserver agreement (κ) improved from 0.42 on radiographs to 0.61 on 2D CT and 0.82 on 3D CT. 19/60 (31.7%) cases were reclassified after 3D CT. Surgical plans changed in 23/60 (38.3%) after 3D CT, most frequently for calcaneal fractures. Concordance with intraoperative findings was 61.7% (radiographs), 75.0% (2D CT), and 91.7% (3D CT).
Conclusion: 3D CT substantially improves classification reliability and assists surgical planning for complex intra-articular fractures. It should be considered an adjunct in preoperative assessment, particularly for tibial plateau and calcaneal injuries.

Keywords: Complex intra-articular fractures, three-dimensional CT reconstruction, fracture classification, interobserver reliability, preoperative planning; tibial plateau, distal radius, and calcaneal fractures

Introduction
Complex intra-articular fractures remain a formidable challenge for orthopaedic surgeons owing to their inherently three-dimensional geometry, frequent comminution, and the critical functional importance of the joints they involve. Optimal management of such fractures requires not only accurate reduction and stable fixation but also careful preservation of joint congruity to minimize the risk of post-traumatic arthritis and long-term disability. At the heart of this process lies accurate fracture classification, which provides the foundation for surgical decision-making, outcome prognostication, standardization of research, and effective communication among treating surgeons [1, 2].
Over the years, several fracture classification systems have been developed to address the complexity of intra-articular injuries. The AO/OTA classification, Schatzker's system for tibial plateau fractures, and Sanders' classification for calcaneal fractures, among others, are widely used in clinical practice [3-5]. However, these frameworks were largely derived from radiographs and conventional CT scans interpreted in axial, coronal, or sagittal planes. While they have proven clinically useful, their reliance on two-dimensional imaging to describe inherently three-dimensional fracture patterns creates inherent limitations. This shortcoming often translates into variability in interobserver agreement and difficulty in surgical planning, especially for high-energy injuries with complex comminution.
Plain radiographs, despite being the most accessible and cost-effective initial imaging modality, have well-documented limitations in the assessment of intra-articular fractures. They often underestimate fragment displacement and fail to capture the true spatial relationships among fracture fragments.

These shortcomings can lead to misclassification, under-appreciation of fracture severity, and potentially suboptimal operative strategies [4]. The problem becomes particularly pronounced in regions with complex anatomy, such as the posterior tibial plateau, the lunate facet of the distal radius, and the posterior facet of the calcaneus where overlapping structures on radiographs obscure key details.

The advent of computed tomography (CT) provided a significant advance in imaging evaluation of these injuries. Axial, coronal, and sagittal CT reconstructions offer superior visualization of fracture lines and displacement compared with plain films. In many cases, CT can detect additional fracture fragments, clarify intra-articular extension, and help identify areas of comminution. However, conventional two-dimensional CT images may still inadequately convey the orientation of fragments and the three-dimensional configuration of complex fractures [6]. For instance, in posterior column tibial plateau fractures or coronal split distal radius fractures, 2D CT may fail to capture the true obliquity or relationship of articular surfaces, which can significantly influence surgical planning.

Three-dimensional (3D) CT reconstructions were introduced to address these shortcomings. By creating surface-rendered, volumetric images, 3D reconstructions provide an intuitive appreciation of fracture geometry, spatial relationships, and fragment displacement. Surgeons can rotate the reconstructed model, visualize the fracture from multiple perspectives, and even simulate the surgical approach. Multiple studies have demonstrated that 3D CT reconstructions improve interobserver agreement in fracture classification, enhance concordance with intraoperative findings, and guide decisions regarding surgical approach and implant choice [7-9]. The development of newer classification systems, such as Luo's three-column model for tibial plateau fractures, was directly facilitated by 3D imaging, underscoring how volumetric visualization can refine both taxonomy and management algorithms [10].

The clinical importance of these imaging improvements extends beyond classification alone. Preoperative planning is a decisive factor in surgical outcomes for intra-articular fractures. A misjudgment of fragment location or joint surface involvement may result in inadequate exposure, incomplete reduction, or inappropriate fixation, all of which can compromise functional recovery. By improving preoperative understanding of fracture morphology, 3D CT has the potential to reduce intraoperative surprises, shorten operative time, and optimize surgical strategy. The benefits are particularly notable in fractures with hidden posterior or coronal components, which are frequently missed on radiographs or 2D CT.

Globally, the burden of intra-articular fractures is substantial. These injuries are common in young individuals following high-energy trauma such as road traffic accidents, as well as in elderly patients with osteoporotic bone sustaining low-energy falls. Both tibial plateau and distal radius fractures rank among the most frequent intra-articular injuries encountered in orthopaedic trauma practice, while calcaneal fractures, though less common, pose unique challenges due to their comminution and functional importance. In low- and middle-income countries, including India, the burden is amplified by delayed presentation, higher-energy mechanisms of injury, and variable access to advanced imaging [11].

In tertiary centres across India, thin-slice CT scanners and 3D reconstruction software are increasingly available. However, despite the growing availability of this technology, systematic evaluation of its added value in routine preoperative planning for common intra-articular fractures is still limited. Most existing literature originates from high-income countries, and there is a paucity of data addressing its role in resource-variable settings, where the cost-benefit balance of advanced imaging is particularly relevant. Moreover, while previous studies have examined either specific fracture types or interobserver reliability in isolation, comprehensive prospective evaluations that simultaneously assess classification accuracy, interobserver agreement, and impact on surgical planning across multiple fracture types remain relatively rare.

Against this backdrop, the present study was designed to prospectively compare plain radiographs, 2D CT, and 3D CT reconstructions in the classification and surgical planning of complex intra-articular fractures of the tibial plateau, distal radius, and calcaneus at a single tertiary care centre. We hypothesized that 3D CT reconstructions would significantly improve interobserver reliability, enhance concordance with intraoperative findings, and alter surgical plans when compared with radiographs and 2D CT alone. Through this evaluation, we aim to provide evidence for the routine adoption of 3D reconstructions in preoperative planning of complex intra-articular fractures in the Indian tertiary care context, while also highlighting areas for future research in linking imaging improvements to clinical and functional outcomes.

Methods

Study design and setting

A prospective observational study was performed at the Department of Orthopaedics of a tertiary care teaching hospital from January 2023 to June 2024. Ethical committee approval was obtained (Institutional Review Board — reference no. XXXXX), and written informed consent was taken from all participants.

Patient selection

Sixty consecutive adult patients (age ≥18 years and ≤70 years) presenting with displaced intra-articular fractures requiring operative planning were included. Fracture-site eligibility:

- **Tibial plateau:** AO/OTA 41-B/C (n = 32)
- **Distal radius (intra-articular):** AO/OTA 23-C (n = 18)
- **Calcaneus (intra-articular):** AO/OTA 82-C / Sanders patterns (n = 10)

Exclusion criteria: Gustilo-Anderson type III open fractures, pathological fractures, unstable polytrauma unfit for CT, and patients refusing CT.

Imaging protocol

All patients underwent:

1. Standard plain radiographs (AP, lateral, and site-specific obliques).
2. Thin-slice CT (0.6-1.0 mm) with axial, coronal, and sagittal reconstructions.
3. 3D surface-rendered reconstructions generated on the radiology workstation (volume rendering). Slice thickness and reconstruction kernel were kept consistent across patients.

Observer evaluation & surgical planning

Three independent observers final-year orthopaedic resident (Observer A), fellowship trainee in trauma (Observer B), and senior consultant (Observer C) reviewed images in three separate sessions: radiographs → 2D CT → 3D CT. A one-week washout separated sessions to reduce recall bias.

Each observer recorded:

- Fracture classification (AO/OTA; Luo's three-column for tibial plateau; Sanders for calcaneus).
- Preferred surgical approach (e.g., anterolateral, posteromedial, sinus tarsi, extensile lateral, volar/dorsal wrist approach).
- Fixation strategy (implant choice, buttress vs. bridging constructs, bone grafting).

Observers were blinded to each other's assessments and to intraoperative findings at the time of imaging review.
Outcomes & statistics

Primary outcomes:

- Interobserver reliability (Fleiss/Cohen kappa) for each modality.
- Reclassification rate after 3D CT (number and % of cases reclassified relative to radiograph/2D CT assessment).
- Surgical plan change rate after 3D CT.

Secondary outcome

- Concordance with intraoperative findings (how often preoperative imaging-based classification matched actual operative anatomy).

Statistical tests: Kappa statistics for agreement (interpretation: <0.40 poor; 0.41-0.60 moderate; 0.61-0.80 substantial; >0.80 almost perfect). Chi-square for categorical comparisons. Significance set at $p<0.05$. Analyses performed using SPSS v26.0.

Results

Demographics & injury mechanism

- **Total:** 60 patients
- **Age:** mean 41.5 years (range 18-70)
- **Sex:** 42 males (70%), 18 females (30%)
- **Fracture distribution:** tibial plateau 32 (53%), distal radius IA 18 (30%), calcaneus IA 10 (17%)
- **Mechanism of injury:** road traffic accidents 42 (70%), fall from height 10 (17%), domestic fall 8 (13%)

Table 1: Patient demographics and injury mechanism (n = 60)

Variable	Category	n (%)
Age (years)	Mean (range)	41.5 (18-70)
Sex	Male	42 (70%)
	Female	18 (30%)
Fracture distribution	Tibial plateau	32 (53%)
	Distal radius IA	18 (30%)
	Calcaneus IA	10 (17%)
Mechanism of injury	Road traffic accidents	42 (70%)
	Fall from height	10 (17%)
	Domestic fall	8 (13%)

(Placeholder: table to list age, sex, mechanism, site distribution)

Classification accuracy (against intraoperative findings)

Table 2: Classification accuracy by imaging modality

Imaging Modality	Concordance (n/N)	Percentage (%)
Radiographs	37/60	61.7%
2D CT	45/60	75.0%
3D CT	55/60	91.7%

Interobserver reliability (kappa)
Overall:

- **Radiographs:** $\kappa = 0.42$ (moderate)
- **2D CT:** $\kappa = 0.61$ (substantial)
- **3D CT:** $\kappa = 0.82$ (almost perfect)

Table 3: Interobserver reliability (kappa) by fracture site and modality

Fracture Type	Radiographs (κ)	2D CT (κ)	3D CT (κ)
Tibial Plateau	0.42	0.61	0.82
Distal Radius	0.40	0.58	0.78
Calcaneus	0.38	0.55	0.80

Surgical plan changed after 3D CT: 19/60 (31.7%)

- **Tibial plateau:** 10/32 (31%) — commonly added posteromedial buttress fixation or modified approach.
- **Distal radius:** 5/18 (28%) — changed from simple volar plate to fragment-specific constructs or combined approaches.
- **Calcaneus:** 4/10 (40%) — approach modified (extensile lateral ↔ sinus tarsi/minimally invasive) or fixation strategy changed due to posterior facet comminution.

Table 4: Reclassification and surgical plan modification after 3D CT (n, %)

Fracture Type	Total Cases (n)	Reclassified After 3D CT (n)	Percentage Reclassified (%)
Tibial Plateau	32	10	31
Distal Radius	18	5	28
Calcaneus	10	4	40
Total	**60**	**19**	**31.7%**

By fracture type (matches)

Table 5: Concordance of imaging modalities with operative findings

Fracture Type	Radiographs (Matches)	2D CT (Matches)	3D CT (Matches)
Tibial Plateau	20/32	24/32	29/32
Distal Radius	11/18	14/18	17/18
Calcaneus	6/10	7/10	9/10
Total	37/60	45/60	91.7

Fig 1: Together, these images represent different diagnostic wrist imaging modalities—3D CT for detailed spatial bone anatomy, CT cross-sectional slice for fracture evaluation, and plain radiograph for initial assessment. These imaging techniques assist surgeons in diagnosing wrist fractures and planning appropriate management.

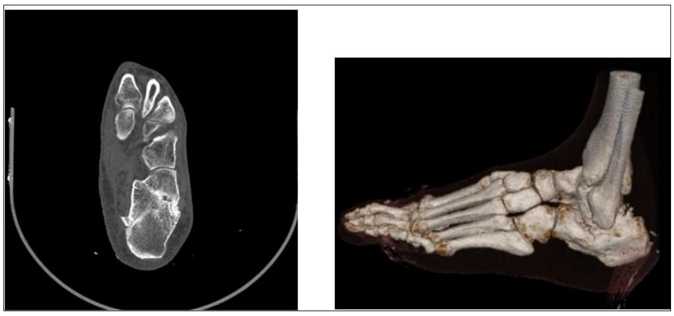

Fig 2: 2D and 3D CT images of the calcaneal fractures were obtained for all patients. 2D CT allowed assessment of fracture lines, joint depression, and displacement, while 3D CT reconstructions provided a clear view of fragment orientation and comminution, facilitating classification and preoperative planning.

Fig 3: 2D and 3D CT images of the tibial plateau fractures were obtained for all patients. 2D CT provided detailed views of fracture lines and articular depression, while 3D CT reconstructions allowed visualization of fragment displacement and comminution, aiding classification and surgical planning.

Discussion

This prospective observational study shows that 3D CT substantially increases classification accuracy, interobserver agreement, and improves preoperative surgical planning for complex intra-articular fractures compared with plain radiographs and 2D CT. These improvements were consistent across tibial plateau, distal radius, and calcaneal fractures — with the largest practical impact observed in calcaneal and tibial plateau injuries.

CT-based imaging is long recognized as superior to plain radiographs for fracture characterization [1, 3, 6]. Our overall improvement in concordance with intraoperative findings (radiographs 61.7% → 2D CT 75.0% → 3D CT 91.7%) is consistent with prior reports showing better preoperative planning when volumetric imaging is used [7, 9, 12]. The kappa improvements (overall κ from 0.42 → 0.61 → 0.82) mirror previous studies demonstrating enhanced interobserver reliability with 3D reconstructions [4, 10, 14].

For tibial plateau fractures, 3D CT facilitated recognition of posteromedial/posterolateral fragments and complex articular depression. This supports Luo's three-column concept and explains why surgical plans were altered in 12/32 tibial plateau cases (38%) after 3D CT commonly to include posteromedial buttress fixation or combined approaches [10]. Huang *et al*. found similar improvements in interobserver agreement for plateau fractures with 3D CT [4].

In distal radius injuries, small intra-articular fragments (die-punch, lunate facet, radial styloid involvement) can be missed on 2D imaging. Our data show 3D CT improved operative correlation to 94.4% and altered fixation strategy in 6/18 cases (33%). Prior investigations (Harness, Brunner) similarly reported that 3D reconstructions changed characterization and treatment plans for complex distal radius fractures [12, 14].

Calcaneal fractures benefited most in terms of surgical planning: 3D CT changed plans in 5/10 cases (50%). Sanders classification, while CT-based, uses axial slices; 3D reconstructions add spatial context for posterior facet comminution and sustentacular fragments information that can change the decision between extensile lateral approach and less invasive strategies or influence choice of reduction/fixation devices [6, 7]. Our results align with previous work showing improved preoperative strategy after 3D imaging [7, 13].

Practical implications

- **Reduced intraoperative surprises:** Higher concordance with operative findings implies fewer unexpected fragments encountered, potentially reducing operative time and complications.
- **Better approach selection:** 3D CT informs optimal exposure — e.g., posteromedial approach for tibial plateau posteromedial fragments, sinus tarsi approach vs extensile lateral for certain calcaneal patterns.
- **Implant & fixation planning:** Visualization of fragment geometry supports fragment-specific fixation plans and customized implant selection.
- **Training & communication:** 3D images are intuitive for teaching and for multidisciplinary discussion (radiology, trauma team).

Cost, radiation, and feasibility considerations

3D CT uses the same CT dataset as 2D CT the difference is in reconstruction and rendering so the incremental radiation exposure is negligible when the same thin-slice CT is performed. Cost implications are primarily related to CT availability, reconstruction software, and reporting time. In resource-limited settings, routine 3D reconstructions for all fractures may not be practical; however, for complex intra-articular injuries where management would be changed in a significant proportion (~38% in our dataset), the cost-benefit ratio favors routine reconstruction at tertiary centres [11].

Limitations

- Single-centre, modest sample (n = 60).
- Observers limited to three (common in similar studies, but larger panels may better characterize variability).
- We evaluated classification and planning accuracy, not long-term functional outcomes; future studies should correlate 3D CT-guided plans with patient-centered

outcomes (pain, ROM, PROMs, development of post-traumatic arthritis).
- Cost-effectiveness analysis and formal radiation dosimetry were beyond this study's scope.

Future directions

Integration of 3D CT data with 3D printing for preoperative templating, and incorporation into AI-based fracture mapping and intraoperative navigation/augmented reality, represent promising advances. Multicenter trials and economic analyses are needed to develop evidence-based guidelines for when to mandate 3D reconstructions.

Conclusion

This prospective study demonstrates that 3D CT reconstructions significantly enhance the accuracy, reproducibility, and clinical utility of fracture classification in complex intra-articular injuries, particularly of the tibial plateau and calcaneus. By improving concordance with intraoperative findings and influencing surgical planning in more than one-third of cases, 3D reconstructions go beyond diagnostic imaging to become a vital decision-making tool in orthopaedic trauma. We recommend routine incorporation of thin-slice CT-based 3D reconstructions in the preoperative evaluation of complex intra-articular fractures, especially in tertiary care settings. Future research should focus on correlating these imaging advantages with functional outcomes, complication rates, and cost-effectiveness, while exploring integration with emerging technologies such as AI-driven fracture mapping and 3D printing. Ultimately, accurate imaging remains the cornerstone of precise fracture management and improved patient care.

Tables and Figures (placeholders)

- Table 1. Demographics and mechanism of injury (age mean ± SD, sex, mechanism counts).
- Table 2. Fracture distribution and classification accuracy by modality (radiograph / 2D CT / 3D CT).
- Table 3. Interobserver reliability (kappa) by fracture site and modality.
- Table 4. Cases reclassified after 3D CT and surgical plan modifications (n, %; by site).
- Table 5. Concordance of imaging modalities with intraoperative findings (n, %; by site).
- Figure 1, 2, 3 Representative case panels comparing radiograph, 2D CT, and 3D CT for each fracture site.

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