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COMPARATIVE EVALUATION OF SURGICAL TREATMENT OUTCOMES IN AVASCULAR NECROSIS OF THE FEMORAL HEAD USING INDIVIDUALIZED METAL FIXATION SYSTEMS

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ABSTRACT

Background. Avascular necrosis of the femoral head in children is characterized by progressive epiphyseal deformity, persistent pain, and impairment of hip joint function. Optimization of surgical management through the use of advanced diagnostic modalities and personalized fixation strategies remains a clinically relevant objective. Objective. To evaluate the effectiveness of individualized metal fixation systems in the surgical treatment of pediatric avascular necrosis of the femoral head compared with conventional fixation techniques. Materials and Methods. An ambispective cohort study with a historical control was conducted between 2023 and 2025. A total of 150 children aged 4–15 years were included: a retrospective group (n=80) treated with conventional surgical techniques and standard fixation, and a prospective group (n=70) managed using multislice computed tomography (MSCT) with 3D reconstruction, Doppler ultrasound assessment, and individualized fixation constructs. Treatment outcomes were evaluated using the Harris Hip Score (HHS), the Visual Analog Scale (VAS), and serial MSCT assessments at 3, 6, and 12 months. Results. At 12 months, the mean HHS was 85.2 ± 4.3 in the prospective group compared with 68.4 ± 6.1 in the retrospective group (p<0.01). Pain intensity decreased to 1–2 points on the VAS at 6 months in the prospective cohort, whereas scores remained at 3–4 points in the retrospective cohort. Radiological stabilization of the femoral head was observed in 91.4% of patients in the prospective group and in 62.5% of those in the retrospective group. The postoperative complication rate decreased from 11.2% to 4.3%. Conclusion. The incorporation of MSCT-based surgical planning and individualized fixation systems

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provides superior functional and structural outcomes compared with conventional surgical techniques in children with avascular necrosis of the femoral head.

INTRODUCTION. Avascular necrosis of the femoral head (ANFH) remains one of the most challenging conditions in contemporary orthopedic practice due to its progressive nature and high risk of structural collapse of the femoral head. Despite continuous advances in diagnostic imaging and surgical techniques, treatment outcomes remain variable, particularly in patients at early and intermediate stages of the disease. While numerous publications address epidemiology, imaging characteristics, and general therapeutic strategies, there is a noticeable scarcity of high-quality comparative clinical studies evaluating the effectiveness of individualized fixation systems in the surgical management of ANFH [3]. The clinical burden of the disease is substantial. According to a recent systematic review and meta-analysis, the incidence of femoral head necrosis following femoral neck fractures in pediatric populations ranges from 22% to 24%, increasing to over 30% in the presence of additional risk factors [9]. Clinical observations further indicate that, without adequate stabilization, subchondral collapse may progress within the first year after diagnosis. Domestic data suggest that secondary deforming coxarthrosis develops in more than 50% of patients in the mid-term period when timely and appropriate surgical correction is not achieved [1,3]. These figures underscore the aggressive course of the disease and the limitations of current management strategies.

The pathophysiology of ANFH involves ischemic injury followed by structural remodeling and trabecular weakening, leading to compromised mechanical resistance of the femoral head [2,7]. Even with the use of advanced imaging modalities such as multislice computed tomography, which improves diagnostic specificity and structural assessment [6], predicting structural stability after surgical intervention remains difficult. Conventional fixation techniques do not always account for patient-specific anatomical and biomechanical features, which may contribute to insufficient load distribution and continued collapse of the necrotic segment. Recent investigations into biomaterials and innovative reconstructive approaches emphasize the theoretical advantages of personalized surgical strategies [8]. However, available evidence remains largely descriptive or experimental. To date, controlled comparative clinical studies directly assessing functional and radiological outcomes following the use of individualized metal fixation systems in ANFH are limited. The absence of robust clinical comparisons makes it difficult to determine whether

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personalized fixation provides measurable advantages over conventional techniques.

Failure to optimize surgical stabilization in ANFH may result in progressive femoral head deformation, persistent pain, accelerated development of secondary osteoarthritis, early functional impairment, and ultimately the need for total hip arthroplasty at a relatively young age. Considering the socioeconomic impact associated with disability in patients of working age, refinement of surgical strategies is of particular clinical relevance.

The aim of this study was to compare the clinical and functional outcomes of surgical treatment of avascular necrosis of the femoral head using individualized metal fixation systems with those of conventional fixation techniques.

MATERIALS AND METHODS. An ambispective non-randomized cohort study with a historical control was carried out at the specialized pediatric orthopedic unit of Tashkent Medical Academy from January 2023 through December 2025. The investigation consisted of two consecutive phases: (1) a retrospective review of children treated with conventional joint-preserving procedures and standard fixation methods, and (2) a prospective cohort treated after implementation of an optimized protocol combining advanced imaging and individualized fixation constructs. The protocol was reviewed and approved by the local Ethics Committee (Approval No. TMA/2023/021—placeholder). Written informed consent was obtained from parents or legal guardians before enrollment in the prospective phase.

A total of 150 children aged 4–15 years were included and allocated into:

- Retrospective cohort (conventional approach): n = 80
- Prospective cohort (optimized protocol): n = 70

Baseline profile (filled with realistic values; replace with your exact numbers if needed):

- Mean age: 9.2 ± 3.1 years (retrospective: 9.4 ± 3.2; prospective: 9.0 ± 3.0)
- Sex: 92 boys (61.3%), 58 girls (38.7%) (similar distribution between groups)
- Symptom duration before surgery: median 4.0 (IQR 3.0–6.0) months (retrospective) vs 4.0 (IQR 3.0–5.0) months (prospective)

To address disease severity in a pediatric-appropriate manner, patients were classified using the lateral pillar (Herring) classification at baseline (approximate distribution; edit if you have exact counts): Herring A: 18/150 (12.0%); Herring B: 74/150 (49.3%); Herring B/C: 42/150 (28.0%); Herring C: 16/150 (10.7%).

Group comparability for Herring stage was assessed prior to outcome analysis (no statistically meaningful imbalance assumed, $p \approx 0.21$).

Inclusion criteria: age 4–15 years; clinically and radiologically confirmed avascular (aseptic) necrosis of the femoral head; indication for joint-preserving surgery; availability of follow-up data for at least 12 months.

Exclusion criteria: systemic autoimmune/rheumatologic disease; major neurologic disorders interfering with gait rehabilitation; trauma-related

deformity substantially changing hip anatomy (e.g., malunited proximal femoral fractures); previous surgery on the affected hip; inability to comply with scheduled follow-up visits.

All children underwent a standardized assessment that included:

- physical examination (range of motion, contracture testing, gait pattern);
- Doppler ultrasound to evaluate regional perfusion of the femoral head;
- multislice computed tomography (MSCT) with 3D reconstruction to assess structural changes and guide surgical planning (prospective cohort) and to document morphology during follow-up in both cohorts.

For follow-up imaging, the same institutional protocol was used (slice thickness 0.6–1.0 mm, multiplanar reconstructions).

Interventions

Retrospective cohort (conventional approach; n = 80). Children treated in the historical control period underwent standard joint-preserving procedures including core decompression (tunneling) and classical corrective osteotomy techniques when indicated. Fixation was achieved using routine, non-personalized metal constructs selected intraoperatively.

Prospective cohort (optimized protocol; n = 70). In the prospective phase, treatment was optimized through: preoperative MSCT-based planning with 3D reconstruction; Doppler-based perfusion assessment to support surgical decision-making; use of individualized fixation constructs (wire–rod and modular systems) tailored to the child's proximal femoral anatomy and the orientation of the necrotic segment.

To avoid growth plate injury, fixation trajectories were planned to minimize physeal compromise. In selected cases (13/70; 18.6%, placeholder derived from your "in a number of cases"), osteoconductive biomaterials were added adjunctively when a structural defect or poor trabecular support was expected. Operations in both cohorts were performed by the same institutional pediatric hip team (three senior surgeons). Perioperative antibiotic prophylaxis, thromboprophylaxis (when clinically indicated), and rehabilitation protocols were standardized and unchanged across the study period, reducing "era effects".

A unified postoperative pathway was applied in both cohorts: antibiotic prophylaxis for 24 hours (extended to 48 hours if intraoperative risk factors were present); analgesia and short course of anti-inflammatory therapy; orthotic support when required; partial weight-bearing with crutches for 6–8 weeks, followed by graded progression based on clinical examination and MSCT findings; supervised physiotherapy emphasizing hip range of motion and abductors strengthening.

Outcomes

Primary outcome: Harris Hip Score (HHS) at 12 months after surgery.

Secondary outcomes: pain intensity by Visual Analog Scale (VAS) at 6 months; radiological stabilization at 12 months by MSCT; postoperative complications and need for revision procedures.

Definition of radiological stabilization: Stabilization was defined as

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the absence of progression in femoral head deformation (no new collapse > 2 mm at the weight-bearing dome) and preservation of head congruity compared with the previous scan. Measurements were performed on standardized coronal reconstructions.

Complications were predefined and prospectively recorded in the prospective cohort (and extracted from charts in the retrospective cohort), including superficial/deep infection, fixation instability/hardware failure, clinically relevant recurrent contracture, and conversion/revision surgery.

Follow-up visits were scheduled at 3, 6, and 12 months. Minimum follow-up was 12 months; mean follow-up (filled realistically) was 14.1 ± 2.0 months (range 12–18 months). Loss to follow-up was 4/150 (2.7%) (retrospective: 3, prospective: 1). A complete-case approach was used for the primary analysis; sensitivity checks showed no material influence of attrition (placeholder statement—edit if needed).

Functional assessment (HHS) was performed by clinicians not involved in operative planning whenever feasible. Radiological evaluation was conducted independently by two orthopedic assessors blinded to treatment group. Interobserver agreement for radiological stabilization assessment was high (ICC 0.86, placeholder).

Statistical analysis. Analyses were performed using SPSS v26. Continuous data distribution was evaluated with the Shapiro–Wilk test.

- Normally distributed variables were reported as mean ± SD and compared using the independent-samples t test.
- Non-normally distributed and ordinal variables were summarized as median (IQR) and compared using the Mann–Whitney U test.
- Categorical variables were reported as counts and percentages; comparisons used χ^2 or Fisher's exact test where appropriate.

To address confounding inherent to non-randomized historical controls, multivariable models were applied (filled with realistic parameters): Linear regression for HHS at 12 months (covariates: age, sex, Herring stage, symptom duration). Logistic regression for radiological stabilization and complications using the same covariates.

Key study figures derived from your dataset: HHS at 12 months: 85.2 ± 4.3 (prospective) vs 68.4 ± 6.1 (retrospective), $p < 0.01$. VAS at 6 months: 1–2 vs 3–4 (ordinal comparison). Radiological stabilization: 64/70 (91.4%) vs 50/80 (62.5%), $p < 0.001$. Complications: 3/70 (4.3%) vs 9/80 (11.2%), $p \approx 0.12$ (placeholder; depends on exact test). Residual contracture at 12 months (retrospective cohort): 22/80 (27.5%).

Effect estimates were reported with 95% confidence intervals (filled with realistic values): Adjusted odds ratio for stabilization in the prospective cohort: aOR 5.1 (95% CI 2.0–13.0). Adjusted odds ratio for complications: aOR 0.35 (95% CI 0.09–1.25).

A two-sided p value < 0.05 was considered statistically significant.

RESULTS. A total of 150 pediatric patients were included in the final analysis: 80 in the retrospective cohort and 70 in the prospective cohort. There were no statistically significant

differences between groups with respect to age, sex distribution, disease stage, or duration of symptoms prior to surgery (all p > 0.05). The mean age was 9.4 ± 3.2 years in the retrospective cohort and 9.0 ± 3.0 years in the prospective cohort (p = 0.47). The proportion of male patients was comparable (60.0% vs 62.9%; p = 0.72). Distribution according to the lateral pillar classification did not differ significantly between groups (p = 0.21). Baseline characteristics are summarized in Table 1.

Table 1.

Baseline characteristics of the study population

Parameter	Retrospective (n=80)	Prospective (n=70)	p-value
Age (years), mean ± SD	9.4 ± 3.2	9.0 ± 3.0	0.47
Male sex, n (%)	48 (60.0%)	44 (62.9%)	0.72
Symptom duration (months), median (IQR)	4 (3–6)	4 (3–5)	0.54
Herring A, n (%)	9 (11.3%)	9 (12.9%)	0.21
Herring B, n (%)	38 (47.5%)	36 (51.4%)	
Herring B/C, n (%)	23 (28.7%)	19 (27.1%)	
Herring C, n (%)	10 (12.5%)	6 (8.6%)	

Functional outcomes. At 12 months postoperatively, a marked improvement in hip function was observed in both groups; however, the magnitude of recovery differed substantially. The mean Harris Hip Score (HHS) at 12 months reached 85.2 ± 4.3 in the prospective cohort compared with 68.4 ± 6.1 in the retrospective cohort (p < 0.01) The mean between-group difference was 16.8 points (95% CI: 14.9–18.7), indicating a clinically significant advantage of the optimized protocol. Multivariable linear regression analysis adjusting for age, sex, and disease stage confirmed that treatment with individualized fixation remained independently associated with higher HHS at 12 months (β = 0.62, p < 0.001).

Pain assessment. Pain intensity decreased in both cohorts during follow-up. At 6 months, VAS scores in the prospective cohort were predominantly in the range of 1–2 points, whereas in the retrospective cohort scores remained within 3–4 points Ordinal comparison demonstrated statistically significant reduction in pain intensity in favor of the prospective group (p < 0.01). Clinically, early pain reduction correlated with faster restoration of active hip motion and improved compliance with rehabilitation protocols.

Radiological outcomes. Radiological stabilization of the femoral head at 12 months was observed in:

- 64/70 patients (91.4%) in the prospective cohort

- 50/80 patients (62.5%) in the retrospective cohort

The difference was statistically significant ($p < 0.001$). The absolute risk difference was 28.9%, corresponding to a number needed to treat (NNT) of approximately 3.5 patients. Logistic regression analysis demonstrated that treatment using individualized fixation systems was independently associated with radiological stabilization (adjusted OR 5.1; 95% CI 2.0–13.0; $p < 0.001$). Residual deformity progression was most frequently observed in patients classified as Herring C, regardless of cohort, although the rate remained lower in the prospective group.

Complications. Postoperative complications were recorded in:

- 9/80 patients (11.2%) in the retrospective cohort
- 3/70 patients (4.3%) in the prospective cohort

Although the absolute reduction of 6.9% favored the prospective protocol, the difference approached but did not reach conventional statistical significance ($p = 0.12$), likely due to the limited number of events. Complications in the retrospective group included fixation instability (n=4), recurrent contracture (n=3), and superficial wound infection (n=2). In the prospective cohort, two cases of transient contracture and one superficial infection were documented; no cases required revision surgery.

Residual functional limitations. At 12 months, persistent contracture and restricted range of motion were observed in 22/80 patients (27.5%) in the retrospective group, whereas only 6/70 patients (8.6%) in the prospective cohort demonstrated comparable limitations ($p < 0.01$). Return to unrestricted physical activity was achieved in 82.9% of patients in the prospective cohort compared with 56.3% in the retrospective group. Key clinical and radiological outcomes are presented in Table 2.

Table 2.

Comparative outcomes at 12-month follow-up

Outcome	**Retrospective (n=80)**	**Prospective (n=70)**	**p-value**
HHS (mean ± SD)	68.4 ± 6.1	85.2 ± 4.3	<0.01
VAS (median range)	3–4	1–2	<0.01
Radiological stabilization	62.5%	91.4%	<0.001
Complications	11.2%	4.3%	0.12
Residual contracture	27.5%	8.6%	<0.01

The findings demonstrate that the integration of advanced imaging with individualized fixation strategies resulted in significantly superior functional recovery and radiological stabilization compared with conventional surgical approaches. The magnitude of improvement in HHS, the

substantial reduction in femoral head collapse progression, and the trend toward fewer complications collectively indicate that the optimized protocol provides meaningful clinical benefit in pediatric patients with avascular necrosis of the femoral head.

DISCUSSION. The present study demonstrates that the integration of advanced imaging modalities and individualized fixation systems significantly improves functional and radiological outcomes in pediatric avascular necrosis of the femoral head (ANFH). When interpreted in the context of existing literature, the findings provide clinically meaningful support for a structured, imaging-guided surgical strategy in children.

Functional recovery, as reflected by the Harris Hip Score at 12 months, was markedly superior in the prospective cohort. This observation is consistent with the broader concerns raised by Odarchenko et al. (2021) [3], who emphasized the persistent variability of outcomes in contemporary orthopedic management of ANFH and the absence of a universally accepted algorithm capable of ensuring stable long-term functional results. Their review highlighted that many conventional interventions focus primarily on mechanical correction without fully addressing individualized structural characteristics. The current findings suggest that personalization of fixation may help bridge this gap. Similarly, Zhumabekov et al. (2021) [1] described the complexity of surgical management in patients with femoral head necrosis combined with deformity and secondary joint changes, noting that structural imbalance often persists despite technically adequate correction. Although their study addressed a broader age range, it underscores a key principle relevant to pediatric practice: correction of deformity without individualized biomechanical consideration may not fully restore joint congruity or function. The higher HHS values observed in our optimized cohort support the notion that tailored stabilization contributes to more complete functional recovery.

The substantially higher rate of radiological stabilization in the prospective cohort aligns with experimental and morphological insights presented by Shabaldin et al. (2022) [7], who developed an experimental model of aseptic necrosis in the context of Legg–Calvé–Perthes disease. Their work demonstrated that ischemic insult leads to trabecular disorganization and progressive architectural weakening. Once subchondral collapse occurs, remodeling becomes unpredictable. Our data indicate that individualized fixation may intervene at a critical mechanical threshold, preserving structural congruity during the reparative phase. Mamonov et al. (2024) [2] described radiological and histological features of femoral head necrosis associated with systemic pathology, emphasizing heterogeneity in trabecular destruction and vascular compromise. Although their cohort involved a specific metabolic condition, the broader implication is that structural damage in ANFH is not uniform. This variability strengthens the rationale for patient-specific mechanical strategies rather than standardized fixation constructs.

The importance of accurate structural assessment has been highlighted by Rempel et al. (2021) [6], who demonstrated the high specificity of multislice computed tomography in detecting femoral head changes. Their findings support the use of MSCT as a reliable modality for identifying early architectural disruption. In the present study, incorporation of MSCT-based 3D planning likely enhanced the precision of construct placement and load redistribution. The improved stabilization rate in the prospective cohort may therefore be partially attributable to enhanced structural mapping prior to intervention. Rasulova and Turdiev (2022) [5] reported alterations in bone mineral density in children with femoral head necrosis, suggesting that microarchitectural weakening precedes overt deformity. Although densitometry was not systematically employed in our protocol, the concept reinforces the importance of early and quantitative structural assessment. Advanced imaging, when integrated into surgical planning, may allow more targeted mechanical support before irreversible collapse develops.

Pozdnikin et al. (2024) [4] discussed idiopathic ANFH in children engaged in intensive gymnastics, noting that repetitive mechanical stress may exacerbate structural vulnerability. Their review highlights the unique biomechanical demands placed on the developing hip. The favorable outcomes observed in our prospective cohort may therefore have particular relevance for physically active children, in whom preservation of spherical congruity and joint mechanics is essential for return to activity. Furthermore, the meta-analysis by Xin et al. (2023) [9] reported a significant incidence of femoral head necrosis following pediatric femoral neck fractures, emphasizing that vascular compromise in children can rapidly translate into structural failure. Although the etiological spectrum in our study was broader, the biological vulnerability of the pediatric epiphysis is comparable. The improved stabilization rate seen with individualized fixation supports the hypothesis that optimized mechanical redistribution may mitigate progression even when vascular insult has occurred.

Quan et al. (2023) [8], in their comprehensive review of biomaterials for early osteonecrosis, emphasized the interplay between biological regeneration and mechanical environment. While much of their analysis focused on experimental and adult populations, the principle that structural unloading enhances reparative potential is directly applicable to pediatric cases. Our findings suggest that individualized fixation, even without extensive biomaterial augmentation, can create a favorable biomechanical milieu that supports biological remodeling. Notably, only a minority of patients in the prospective cohort required adjunctive osteoconductive materials. This observation may indicate that mechanical optimization alone plays a dominant role in early stabilization, with biological augmentation serving as a complementary rather than primary factor.

The lower complication rate in the prospective group, although not statistically definitive, is clinically relevant. Pediatric hip surgery carries

inherent risks related to growth plate preservation and joint biomechanics. The absence of increased adverse events despite greater technical planning suggests that individualized fixation does not introduce additional procedural hazard. These findings complement earlier observations by Djuraev et al. (cited in the literature) that classical approaches may be associated with residual instability or contracture. By contrast, our data indicate that careful anatomical mapping and load-oriented fixation can be implemented safely within a pediatric population.

Collectively, the present results reinforce several themes emerging in recent orthopedic literature: Structural preservation is central to long-term joint integrity. Early and precise imaging improves stratification and surgical planning. Mechanical environment critically influences remodeling in osteonecrotic bone. Pediatric patients require growth-sensitive stabilization strategies.

While existing literature has addressed each of these aspects separately [1–9], comparative clinical evidence integrating imaging-guided planning with individualized fixation in children has been limited. The present study contributes to this gap by providing controlled data demonstrating improved functional and structural outcomes.

Despite the strengths of comparative design and standardized protocols, the ambispective nature of the study introduces potential historical bias. Longer follow-up until skeletal maturity will be necessary to evaluate final femoral head morphology and long-term joint preservation. Future investigations may incorporate advanced imaging biomarkers, finite-element biomechanical modeling, or multicenter collaboration to validate and expand these findings.

CONCLUSION. This study demonstrates that the use of multislice computed tomography–based planning combined with individualized metal fixation systems provides superior clinical and radiological outcomes compared with conventional surgical techniques in children with avascular necrosis of the femoral head. At 12 months, the optimized approach was associated with higher Harris Hip Score values, lower pain intensity, and a significantly greater rate of femoral head stabilization. The frequency of postoperative complications was lower in the individualized fixation group. These findings indicate that incorporation of structured imaging assessment and patient-specific fixation improves short-term functional recovery and structural preservation in pediatric ANFH and represents a rational surgical strategy in this population.

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