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RADIOGRAPHIC COLLAPSE AS A CRITICAL THRESHOLD IN THE CHOICE BETWEEN TUNNELING AND TOTAL HIP REPLACEMENT: A MULTICENTER ANALYSIS OF TACTICAL DECISIONS

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Background. Avascular necrosis (AVN) of the femoral head is a therapeutic dilemma between joint-preserving procedures (tunneling) and total hip replacement (THR). Lack of clear radiological thresholds complicates surgical choice and delays prosthesis timing.

Objective: To assess whether the degree of radiographic subchondral collapse can guide surgical strategy in femoral head AVN.

Methods. A multicenter cohort study (2020–2025) analyzed 126 AVN cases in Odesa and Kyiv. Patients were assigned to tunneling (n = 51) or THR (n = 75). Subchondral collapse was measured, with 2 mm as threshold. Outcomes: Harris Hip Score (HHS), Visual Analogue Scale (VAS), revision rates. Logistic regression identified predictors of surgical choice.

Results. Collapse > 2 mm strongly correlated with THR (85.3%), while < 2 mm favored tunneling (78.4%). The 2 mm cutoff had high predictive value (OR=5.6). Age > 50 and bilateral disease were independent predictors of THR. Both groups improved, but HHS was higher after THR ($p < 0.01$). Military service and post-COVID steroid use emerged as additional ischemic risk factors.

Conclusions. Subchondral collapse > 2 mm is a clinically relevant threshold favoring THR. Patients < 40 years with minimal collapse and unilateral AVN are best suited for joint-preserving options, including potential MSC therapy. Integration of the 2 mm criterion into surgical algorithms may optimize timing and support predictive precision-medicine models.

Keywords: avascular necrosis, femoral head, radiographic collapse, surgical strategy.

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РЕНТГЕНОЛОГІЧНИЙ КОЛАПС ЯК КРИТИЧНИЙ ПОРІГ У ВИБОРІ МІЖ ТУНЕЛІЗАЦІЄЮ ТА ТОТАЛЬНИМ ЕНДОПРОТЕЗУВАННЯМ КУЛЬШОВОГО СУГЛОБА: МУЛЬТИЦЕНТРОВИЙ АНАЛІЗ ТАКТИЧНИХ РІШЕНЬ

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Аваскулярний некроз (AVN) голівки стегнової кістки залишається складною клінічною проблемою, особливо в разі вибору між органозберігаючими методами та тотальним ендопротезуванням (THR). У мультицентровому когортному дослідженні (2020–2025, Одеса і Київ) проаналізовано 126 випадків AVN: 51 пацієнту виконано тунелізацію, 75 – THR. Ключовим критерієм була величина субхондрального колапсу: > 2 мм асоціювався з вибором THR (85,3%), < 2 мм – із тунелізацією (78,4%), OR = 5,6. Незалежними предикторами THR стали вік понад 50 років і двобічне ураження. В обох групах відзначено покращення, проте Harris Hip Score після операції був достовірно вищим у пацієнтів із THR. Додатковими чинниками ризику виявлено військову службу та пост-COVID стероїдну терапію. Колапс понад 2 мм слід розглядати як порогове значення для вибору THR, тоді як молоді пацієнти з мінімальним ураженням залишаються кандидатами для органозберігаючих підходів, включно з MSC-терапією.

Ключові слова: аваскулярний некроз, голівка стегнової кістки, рентгенологічний колапс, хірургічна тактика.

Introduction

Avascular necrosis (AVN), also referred to as osteonecrosis, is a progressive pathological process resulting from impaired blood supply to the bone tissue, leading to ischemia, osteocyte death, and subsequent structural destruction of the bone [1]. The femoral head is the most commonly affected site, although AVN may also involve the humeral head, knee, talus, and other epiphyseal zones [1; 2]. The main etiological factors include trauma, prolonged systemic corticosteroid use, alcohol abuse, sickle cell anemia, hypothermia, chronic overloading, and idiopathic cases [3]. In clinical practice, early detection of radiographic signs of collapse is crucial for prognosis and therapeutic strategy selection. The term "radiographic collapse" encompasses three primary features: subchondral collapse – initial disruption of the subchondral bone plate integrity; the crescent sign – a linear radiolucent zone beneath the subchondral bone indicating detachment of the necrotic segment; and flattening – the loss of normal joint surface sphericity,

which reflects mechanical decompensation and progressive structural failure [4]. These imaging changes are associated with a high risk of secondary osteoarthritis and often necessitate surgical intervention.

The core of the therapeutic dilemma in femoral head AVN lies in the choice between joint-preserving interventions (e.g., core decompression or tunneling) and radical approaches such as total hip replacement (THR) [5]. This decision is complicated by the lack of a clearly defined clinical "threshold" that would signal the need to transition from conservative or preserving management to prosthetic surgery. On one hand, decompression is minimally invasive, can be effective in early-stage AVN (ARCO I–II) [1; 6], preserves the native joint, and delays or avoids prosthesis implantation, particularly in younger patients. On the other hand, AVN is frequently progressive, and femoral head involvement often leads to subchondral collapse (crescent sign, flattening), after which the efficacy of joint-preserving techniques markedly decreases [1; 5]. However, determining the exact tipping point is subjective – no universal criteria exist that definitively indicate the appropriateness of proceeding to THR. In clinical practice, the decision depends not only on the AVN stage but also on patient age, pain level, functional impairment, comorbidities, expected implant longevity, procedural availability, and surgical expertise [7]. This multifactorial nature leads to clinical uncertainty, which embodies the core of the dilemma of how long to persist with joint preservation without missing the optimal window for prosthetic intervention.

Objective: To determine whether radiographic collapse is a reliable prognostic marker for selecting surgical strategy.

Materials and Methods

This study was conducted as a multicenter retrospective-prospective cohort analysis based on data from specialized orthopedic centers in Odesa and Kyiv between 2020 and 2025. The total sample included 126 clinical cases of avascular necrosis (AVN) of the femoral head, of which 51 patients underwent joint-preserving interventions (tunneling/core decompression), and 75 underwent total hip replacement (THR). Inclusion criteria were: age between 18 and 65 years, diagnosed AVN of the femoral head at Ficat stage II–III [8], availability of complete imaging data (X-ray, CT, or MRI) prior to surgery, and having undergone one of the two surgical procedures – core decompression/tunneling or THR.

Patients with destructive lesions of the femoral neck of different etiology (e.g., metastatic or infectious origin), with associated hip joint deformities or rheumatic conditions, as well as those without postoperative imaging follow-up, were excluded from the study. All included patients underwent radiographic assessment of subchondral collapse according to the JOA [9], ARCO [6], and Ficat [8] classifications. Patients were further stratified based on collapse severity: 0–2 mm or greater than 2 mm. Treatment effectiveness was evaluated through secondary clinical outcomes, including the need for revision surgery, functional outcomes using the Harris Hip Score [10], and pain intensity measured via the Visual Analogue Scale (VAS) [11].

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. The study protocol No. 10/22 was approved by the Ethics Committee on September 5, 2022.

Informed consent was obtained from all individual participants included in the study. Ethical approval was obtained from the relevant ethics committees of all participating institutions

Statistical analysis was performed using R software [12]. ANOVA was used to compare means between groups, while correlation analysis assessed the relationship between collapse severity and functional outcomes. Homoscedasticity was tested using Levene's test. If data did not follow a normal distribution, nonparametric methods were applied, including the Mann–Whitney U test and Spearman's correlation [16]. The critical level of statistical significance was set at $p < 0.05$.

Research results and their discussion

The average age of patients across the total cohort was 46.7 ± 9.1 years. In the tunneling group, the average age was lower – 41.3 ± 8.5 years – while in the THR group, it was 50.2 ± 7.3 years ($p < 0.01$). The sex distribution showed a male predominance: 84 men (66.7%) vs. 42 women (33.3%), with AVN in men more often linked to external risk factors. Major risk factors included long-term or systemic corticosteroid use (41.3% of cases), alcohol abuse (28.6%), previous trauma (18.3%), and idiopathic forms with no clearly established etiology (11.8%). In some patients, especially younger men, multiple triggers were present, notably a combination of corticosteroid therapy and alcohol use.

During the period 2020–2025, amid the full-scale war in Ukraine, an increased incidence of femoral head AVN was noted among military personnel, correlating with combat-specific risk factors. Among the military subgroup ($n = 38$; 30.2% of the total cohort), two key risk factors predominated: chronic marching overload of the hip joints and trench-induced hypothermia. Continuous axial loading from carrying full gear, especially in rugged terrain, led to microtrauma in the epiphyseal region, and compromised microcirculation contributed to ischemic processes in the femoral head. Additionally, prolonged exposure to cold and wet environments (trenches, bunkers) without the ability to warm up caused trench-related hypothermia, exacerbating vascular dysfunction and ischemic damage. In 21 cases (55.3% of the military subgroup), marching overload was the primary identified factor, while in 10 cases (26.3%) both risk factors were combined. The remaining military patients had idiopathic or trauma-related AVN. These findings highlight the need to classify combat conditions as a distinct pathogenetic domain in the risk structure for AVN in populations exposed to chronic physical and thermal stress.

Coronavirus infection (COVID-19), especially in patients who experienced moderate to severe disease requiring hospitalization, emerged as an additional risk factor for AVN of the femoral head in both civilian and mili-

tary populations between 2020 and 2025. In the total cohort (n = 126), 19 patients (15.1%) had a confirmed history of COVID-19; among them, 13 had received systemic corticosteroid therapy (dexamethasone, methylprednisolone) in doses exceeding the cumulative risk threshold (> 2 g per course). In this subgroup, AVN followed a typical steroid-associated course, debuting 4–12 months post-recovery. Military personnel recovering from COVID-19 often faced adverse recovery conditions: limited access to rehabilitation, early return to physical strain, which, combined with post-COVID endothelial dysfunction, may have intensified ischemic processes in the femoral head. Among the military subgroup with AVN, 6 out of 38 cases (15.8%) had a history of COVID-19, and 4 of these had received steroids. Thus, COVID-19, whether as a direct factor or mediated through steroid therapy, represents a significant component of the modern AVN risk profile, especially under wartime conditions with limited medical support.

The frequency of bilateral AVN was 34.1%. Among patients with bilateral disease, total hip replacement was more often selected when at least one hip exhibited a collapse greater than 2 mm. These findings underscore the significant influence of age, sex, and modifiable risk factors in shaping the clinical profile of AVN patients and guiding surgical decision-making.

Figure 1 illustrates typical radiographic features of AVN in patients who subsequently underwent tunneling (a) or total hip replacement (b).

In the vast majority of cases where subchondral collapse of the femoral head was less than 2 mm, clinicians opted for a joint-preserving strategy, particularly tunneling: this procedure was performed in 78.4% of patients with minimal collapse, indicating a preference for early surgical intervention aimed at preserving the anatomical integrity of the joint. Conversely, in cases with pronounced collapse exceeding 2 mm, the rate of total hip replacement (THR) reached 85.3%, confirming its dominance as the treatment of choice in settings of substantial joint structure damage.

Analysis of the treatment strategy in relation to the degree of collapse, patient age, and bilateral involvement revealed statistically significant associations: for example, increasing age over 50 years ($p < 0.01$) and the presence of bilateral AVN ($p = 0.03$) correlated with a higher likelihood of receiving THR, while tunneling was more frequently performed in younger patients with unilateral disease and minimal structural damage.

Comparison of functional outcomes between both groups demonstrated a marked reduction in pain (VAS score) and improvement in Harris Hip Score (HHS) postoperatively in both approaches. However, in the THR group, the mean HHS was significantly higher (87.2 ± 6.1 vs. 79.4 ± 8.3; $p < 0.01$), indicating greater short-term efficacy of arthroplasty in the setting of advanced joint destruction.

Logistic regression modeling of factors influencing treatment choice identified independent predictors for the assignment of THR: collapse > 2 mm (OR = 5.6; 95% CI: 2.8–11.4), age over 50 years (OR = 2.9; 95% CI: 1.4–6.0), and bilateral involvement (OR = 2.1; 95% CI: 1.0–4.4). Meanwhile, a collapse of < 2 mm and age under 40 years significantly increased the probability of selecting tunneling as the primary treatment approach.

The logistic regression equation describing the probability of total hip replacement (THR) assignment is as follows:

$$logit(p) = 0.343 + 2.436 \times (collapse > 2\ mm) + 1.65 \times \\ \times (age > 50) + 0.16 \times (bilaterality),$$

where logit(p) is the logarithm of the odds ratio of being assigned to THR versus undergoing tunneling, and all variables are binary (0 or 1). The greatest contribution to the decision in favor of THR comes from pronounced collapse (> 2 mm), followed by age over 50 years. Bilaterality has a minor, statistically non-significant impact on the model.

Figure 2 illustrates how the probability of assigning THR changes depending on the degree of collapse and the patient's age.

The results obtained highlight the importance of a multifactorial approach when selecting a surgical strategy in patients with avascular necrosis (AVN) of the femoral head.

Discussion. The findings confirm the pivotal role of radiographic collapse severity as a determinant of surgical strategy in AVN of the femoral head. Consistent with the recommendations of the Japanese Orthopaedic Association (JOA, 2019) [9], which advocate for joint-preserving interventions at early stages (ARCO I–II) before subchondral fracture occurs, our data demonstrate a marked increase in the frequency of total hip replacement (THR) once the collapse exceeds 2 mm. A similar stance is taken by the German Society for Orthopaedics and Trauma Surgery (DGOU, 2019) [13], which emphasizes the limited value of decompression after the appearance of the crescent sign or flattening of the joint surface. In our study, patients with

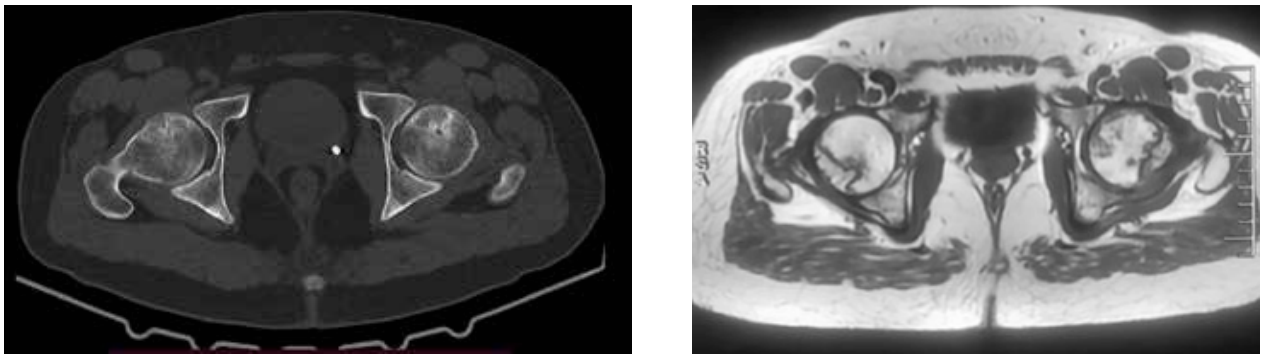

Fig. 1. Imaging of AVN in patients who underwent tunneling (a) and total hip replacement (b)

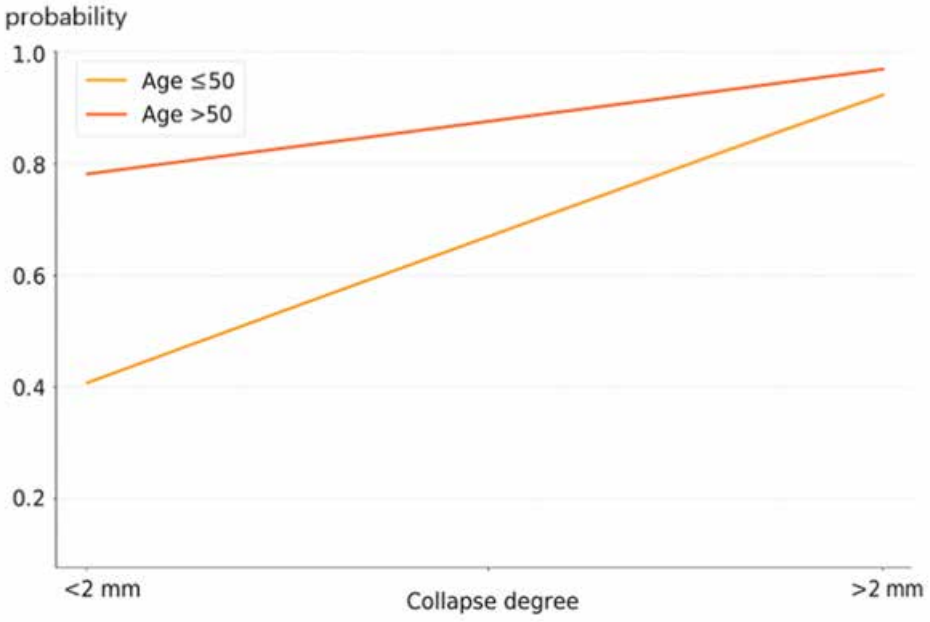

Fig. 2. Influence of Collapse Severity and Patient Age on the Choice of Surgical Treatment Method

a collapse of < 2 mm most frequently underwent tunneling (78.4%), whereas THR was the dominant approach in those with a collapse > 2 mm (85.3%), a pattern confirmed by a logistic regression model in which this parameter had the highest predictive value (OR = 5.6).

Analysis of age and anatomical factors also reveals a progressive shift in clinical decision-making toward THR in patients over 50 years of age and in those with bilateral lesions. These data are in line with European guidelines suggesting that in elderly patients with functional deficits and a high risk of AVN progression, prosthetic replacement should not be delayed in favor of potentially ineffective procedures [13; 14]. Conversely, younger patients with minimal collapse (< 2 mm), particularly those without bilateral involvement, constitute an optimal group for joint-preserving treatments.

Particularly noteworthy is the identification of specific populations, such as military personnel, who showed an increased incidence of AVN due to the combination of marching loads and trench hypothermia. These factors may represent a distinct pathogenetic category insufficiently addressed in current international guidelines. Furthermore, a subset of patients (15.1%) had a history of COVID-19, particularly those who received corticosteroid therapy, aligning with recent clinical observations of post-COVID AVN [15].

From a clinical standpoint, our findings refine the threshold for effective tunneling – specifically, a collapse of 2 mm appears to be a critical limit: beyond this point, joint-preserving methods rarely achieve functional success and merely delay THR without significantly reducing pain or improving quality of life [1; 5]. This enables faster strategic decision-making in daily practice based not only on ARCO or Ficat staging but also on precise measurement of radiographic collapse, patient age, and bilaterality.

However, several limitations should be acknowledged. First, the retrospective component of the study limits control over the quality and standardization of initial imaging. Second, despite uniform inclusion criteria, the tunneling technique may have varied between centers in real-life settings, potentially affecting the results. Third, radiographic assessments inherently involve a subjective component, even when multiple reviewers are involved. Despite these issues, the overall consistency of our data with international guidelines, the strong predictive power of the model, and the justified clinical threshold (< 2 mm) support the relevance of these findings for standardizing surgical decision-making in AVN.

The use of autologous mesenchymal stem cells (MSCs) in the treatment of femoral head AVN is increasingly discussed in the literature as a promising joint-preserving strategy, especially in the early stages of the disease (ARCO I–II) [6]. The mechanism of MSC action involves stimulation of angiogenesis, osteogenesis, and repair of the ischemic area through paracrine signaling and direct participation in bone tissue regeneration. These cells are typically derived from bone marrow and, less frequently, from adipose tissue, and are injected into the necrotic zone through a tunnel created during core decompression.

Comparative studies, including randomized controlled trials, have shown that combining MSCs with decompression reduces the risk of collapse, improves functional outcomes, and delays or even eliminates the need for THR, particularly in young patients with limited necrotic involvement [16]. Certain guidelines, including those from India and China [17; 18], already recommend the inclusion of MSCs as an adjunct to tunneling in the absence of subchondral collapse.

Nonetheless, clinical implementation of this technology faces several barriers. First, not all orthopedic centers have the laboratory capacity for MSC isolation and culture, and commercially available products remain expensive. Second, there is no standardization of protocols (cell source, dose, delivery method, quality control), complicating inter-study comparisons. Third, despite numerous promising case series, the current level of evidence is insufficient to

recommend MSCs as a standard treatment – particularly in advanced AVN stages, where anatomical collapse limits the effectiveness of regenerative approaches.

Therefore, MSC therapy in AVN appears promising, particularly in younger patients with limited ischemic damage and no signs of subchondral collapse. However, its effectiveness, dose-dependence, long-term outcomes, and cost-effectiveness require further large-scale studies, standardization, and regulatory approval before it can become part of routine orthopedic practice.

Conclusions

The results of this multicenter analysis allow us to define clinically meaningful threshold values for selecting a surgical strategy in femoral head AVN. Specifically, a subchondral collapse > 2 mm is significantly associated with the preference for THR and with diminished efficacy of joint-preserving procedures. Age over 50 and bilateral involvement also shift the surgical approach toward THR, while tunneling remains appropriate in patients with a collapse < 2 mm and under the age of 40, potentially combined with MSC therapy. Based on these findings, we recommend including radiographic collapse assessment as a mandatory criterion in standardized AVN management algorithms alongside clinical factors, ARCO/Ficat staging, and MRI findings. Establishing a clear 2 mm threshold as a critical point for altering surgical strategy enhances clinical decision-making, promotes unified practices, and may be incorporated into relevant national clinical guidelines.

Future Directions. Given the results obtained, the next logical step is validating the proposed logistic model for surgical decision-making in an independent prospective AVN cohort to confirm its predictive accuracy and clinical applicability in real time. Additional inclusion of biological markers of ischemia, bone resorption, and repair (e.g., P1NP, CTX, VEGF, D-dimer) may enhance patient stratification and serve as early indicators of necrosis progression. Special attention should also be given to assessing individual hip joint load, using tools such as inertial sensors or gait analysis platforms, to integrate biomechanical factors into the clinical risk model. Based on these parameters, the development of a machine-learning decision algorithm that integrates radiological, biochemical, clinical, and functional variables could automate and personalize surgical strategies. Such an approach aligns with the principles of precision medicine and holds the potential to significantly improve the rationale and outcomes of AVN treatment across diverse clinical settings.

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