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THE PATHOPHYSIOLOGY AND INTERVENTIONS OF AVASCULAR NECROSIS IN FEMORAL HEAD: A SYSTEMATIC REVIEW OF CONSERVATIVE AND SURGICAL MANAGEMENT OPTIONS

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ABSTRACT

Avascular necrosis (AVN) of the femoral head is a debilitating condition characterized by the death of bone tissue due to interrupted blood supply, often leading to joint collapse and severe functional impairment. The condition poses significant challenges for both diagnosis and management, as its etiology is multifactorial, ranging from trauma to corticosteroid use and idiopathic causes. This systematic review aims to comprehensively analyze the pathophysiology of AVN and evaluate the effectiveness of conservative and surgical management strategies. A systematic search of PubMed, Cochrane, and Scopus databases followed the PRISMA guidelines. Studies published between 2010 and 2024 were included based on predefined inclusion criteria focusing on clinical outcomes of treatment modalities. Conservative approaches such as pharmacotherapy, core decompression without grafting, and physiotherapy were compared with surgical interventions like bone grafting, osteotomies, and total hip arthroplasty. Findings indicate that early-stage AVN responds well to conservative measures, whereas advanced cases often require surgical interventions. Emerging technologies, including stem cell therapies and 3D-printed implants, show promise but need further investigation. Despite advancements, gaps in the understanding of optimal treatment protocols persist. This review highlights the

importance of tailored treatment strategies to preserve joint function and improve patient outcomes. Future research should focus on bridging these gaps and developing standardized guidelines for managing AVN.

Keywords: *Avascular necrosis, Femoral head, Conservative management, Surgical interventions, Pathophysiology, Joint preservation, Total hip arthroplasty, Bone grafting.*

1. Introduction

Avascular necrosis (AVN) of the femoral head is a progressive orthopaedic condition caused by the disruption of blood supply to the bone, leading to cellular death, structural compromise, and eventual joint dysfunction.[1] Globally, AVN accounts for a significant proportion of non-traumatic hip replacements, affecting individuals predominantly in their third to fifth decades of life.[2] The condition is of considerable concern due to its debilitating impact on mobility and quality of life, as well as the substantial socioeconomic burden associated with its treatment.[3]

AVN is classified into traumatic and non-traumatic etiologies. Traumatic causes, such as femoral neck fractures and dislocations, directly impair blood flow to the femoral head. At the same time, non-traumatic factors, including corticosteroid use, alcohol abuse, and systemic diseases, involve complex pathophysiological mechanisms that compromise vascular integrity.[4] These etiologies often overlap, making the condition multifactorial and challenging to diagnose in its early stages.[5]

Early detection of AVN is critical for effective management and preservation of joint function. Advances in imaging modalities, such as magnetic resonance imaging (MRI), have facilitated the identification of subclinical stages, enabling timely intervention.[6] However, the clinical presentation is often nonspecific, with patients initially experiencing vague groin pain that progresses to severe disability as the disease advances.[7]

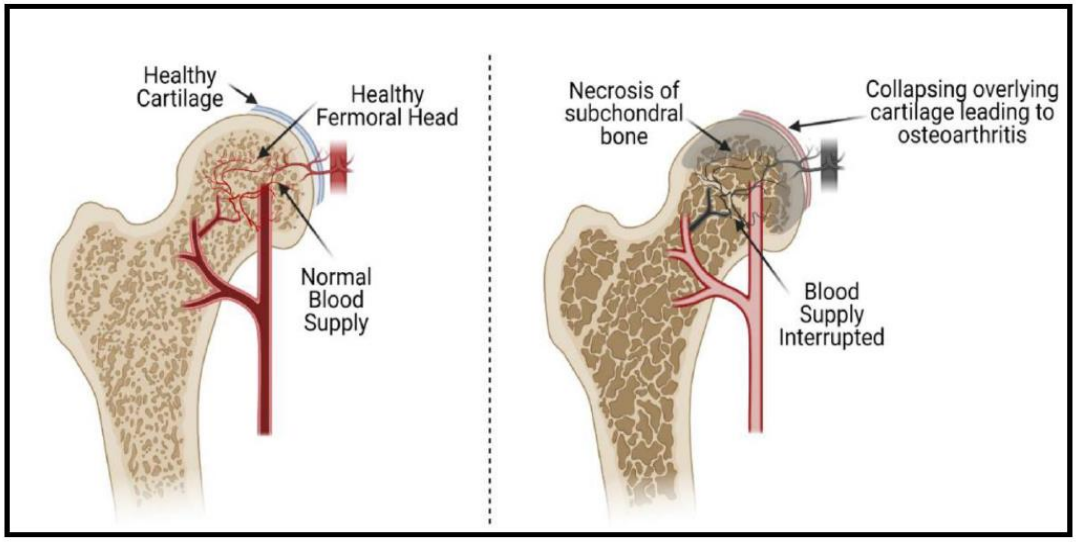

Figure 1: Avascular necrosis of the femoral head.

AVN management strategies can be broadly categorised into conservative and surgical options, with the choice of intervention largely dependent on the stage of the disease. Conservative treatments, including pharmacological agents like bisphosphonates, anticoagulants, and physiotherapy, aim to alleviate symptoms and delay progression in the early stages.[8] Surgical interventions, such as core decompression, bone grafting, and total hip arthroplasty (THA), are generally reserved for advanced cases where joint preservation is no longer feasible.[9] Despite these advancements, there remains a lack of consensus on the optimal treatment protocol, with considerable variability in outcomes across different modalities.[10]

The need for a systematic understanding of AVN's pathophysiology and management has become increasingly crucial as novel therapies, such as stem cell-based approaches and 3D-printed implants, emerge.[11] These advancements can potentially revolutionize the treatment landscape but require rigorous evaluation to establish their efficacy and safety.[12] Furthermore, the long-term outcomes of various interventions, particularly in younger patients, remain poorly defined, necessitating further research.[13]

2. Methods

This systematic review adhered to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines.[14] A structured search strategy was employed to identify studies relevant to the femoral head's pathophysiology and avascular necrosis (AVN) management.

2.1 Search strategy

PubMed, Scopus and Cochrane Library databases were searched for studies published between January 2010 and December 2024. Keywords included "avascular necrosis," "femoral head," "conservative management," "surgical interventions," "pathophysiology," and "joint preservation." Boolean operators (AND, OR) were applied to refine search results.[15] Additionally, the reference lists of key articles were screened to identify relevant studies not captured in the initial search.

2.2 Inclusion and Exclusion criteria

2.2.1 Inclusion criteria

- Peer-reviewed articles published in English.
- Studies reporting on pathophysiology or management strategies for AVN in the femoral head.
- Clinical trials, cohort studies, case-control studies, and meta-analyses.

2.2.2 Exclusion criteria

- Animal studies or in vitro research.
- Articles lacking detailed clinical data.
- Studies focusing on AVN in anatomical locations other than the femoral head.[16]

Table 1: Summary of Inclusion and Exclusion Criteria.

Criteria	Inclusion	Exclusion
Language	English	Non-English
Study design	Clinical trials, cohort studies, meta-analyses	Animal or in vitro research
Population	Patients with AVN in the femoral head	AVN in other anatomical locations
Outcomes reported	Pathophysiology or management strategies	Studies lacking clinical data

2.3 Study selection

The search yielded 1,245 articles. After removing duplicates (n=372), titles and abstracts were screened for relevance, resulting in 198 articles for full-text review. Following applying inclusion and exclusion criteria, 93 studies were selected for final analysis.[17]

2.4 Data Extraction and Quality assessment

A standardized data extraction form collected information on study design, sample size, patient demographics, intervention methods, and outcomes. Quality assessment was performed using the Newcastle-Ottawa Scale for observational studies and the Cochrane Risk of Bias tool for randomized controlled trials.[18]

2.5 Statistical analysis

Data synthesis involved qualitative analysis and meta-analysis when applicable. Heterogeneity was assessed using the I^2 statistic, and results were expressed as pooled odds ratios (OR) or mean differences (MD) with 95% confidence intervals (CI).[19]

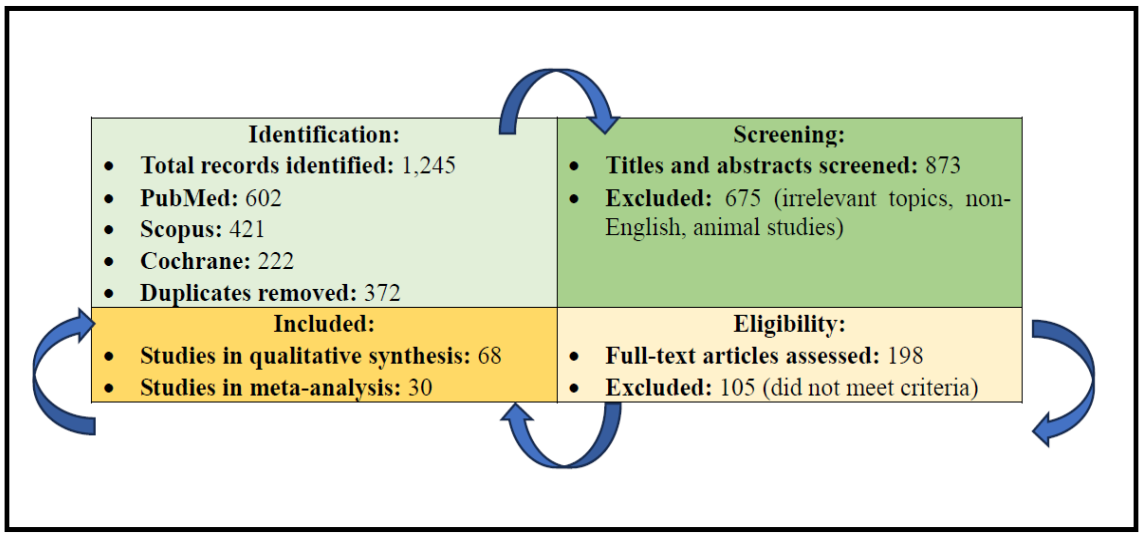

Figure 2: Flowchart: PRISMA Study Selection Process.

3. Pathophysiology of avascular necrosis

Avascular necrosis (AVN), or osteonecrosis, is a progressive condition resulting from ischemic injury to bone tissue due to impaired blood supply. This pathological process involves a multifactorial etiology that can lead to the collapse of subchondral bone and subsequent joint dysfunction.[20]

3.1 Etiology and Risk Factors

The etiology of AVN is broadly categorized into traumatic and non-traumatic causes. Traumatic causes include femoral neck fractures and hip dislocations, which directly disrupt blood flow to the femoral head.[21] Non-traumatic factors, such as chronic corticosteroid use, alcohol abuse, smoking, and systemic conditions like sickle cell disease and lupus, contribute

to microvascular occlusion and reduced bone perfusion.[22] Idiopathic cases are also reported where no identifiable risk factor exists.[23]

3.2 Vascular Disruption and Ischemia

The primary pathophysiological mechanism in AVN is vascular compromise, leading to ischemia and subsequent bone necrosis. The femoral head relies on the lateral and medial circumflex femoral arteries for its blood supply, and any disruption to these vessels can cause localized ischemia.[24] This results in hypoxic damage to osteocytes and bone marrow, triggering necrosis.

3.3 Cellular and Molecular mechanisms

Hypoxia-induced necrosis initiates a cascade of cellular events, including:

- **Osteocyte apoptosis:** Reduced oxygen levels lead to the death of osteocytes, which are critical for bone remodelling.[25]
- **Adipogenesis:** Hypoxia promotes the differentiation of mesenchymal stem cells into adipocytes, further reducing osteoblast activity.[26]
- **Inflammatory response:** Necrotic bone tissue releases pro-inflammatory cytokines, such as interleukin-6 (IL-6) and tumor necrosis factor-alpha (TNF-α), exacerbating local tissue damage.[27]

Table 2: Key Pathophysiological Mechanisms in AVN.

Mechanism	Details
Vascular compromise	Disruption of blood supply to the femoral head (e.g., trauma, thrombosis)
Osteocyte apoptosis	Cell death due to hypoxia, impairing bone remodelling
Adipogenesis	Mesenchymal stem cell differentiation into adipocytes, reducing bone formation
Inflammatory cytokines	Release of IL-6 and TNF-α, causing further tissue damage
Subchondral fractures	Structural collapse due to trabecular bone weakening

3.4 Structural changes in bone

As necrosis progresses, the affected bone undergoes structural weakening due to the loss of trabecular integrity. This is particularly evident in the subchondral region, which bears significant mechanical stress.[28] Over time, subchondral fractures and collapse of the articular surface lead to joint instability and osteoarthritis.[29]

3.5 Stages of AVN

The progression of AVN is classified into distinct stages, commonly using the Ficat-Arlet classification:

- **Stage I:** Normal radiographs; MRI shows oedema and ischemia.
- **Stage II:** Sclerosis and cystic changes without femoral head collapse.
- **Stage III:** Subchondral fracture with partial collapse.
- **Stage IV:** Advanced collapse with secondary osteoarthritis.[30]

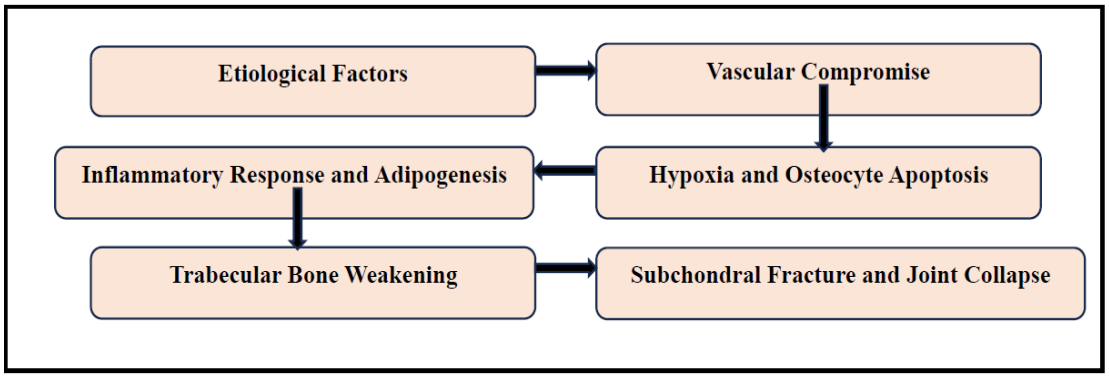

Figure 3: Flowchart: Progression of Pathophysiology in AVN.

4. Conservative Management of Avascular Necrosis *(800–1000 words)*

Conservative management of avascular necrosis (AVN) is primarily aimed at alleviating symptoms, slowing disease progression, and delaying surgical intervention, particularly in the early stages of the condition. These approaches best suit patients with minimal femoral head collapse or those contraindicated for surgery.[31]

Table 3: Summary of Conservative Management Options for AVN.

Intervention	Mechanism	Clinical Evidence
Bisphosphonates	Inhibits osteoclast activity, prevents bone resorption	40% reduction in collapse rates in early-stage AVN[33]
Anticoagulants	Reduces vascular occlusion, improves perfusion	Effective in hypercoagulable states (e.g., sickle cell)[34]
Statins	Reduces marrow lipid deposition, enhances microcirculation	Experimental efficacy in animal models[36]
Physiotherapy	Enhances mobility, reduces joint stress	Improves functional outcomes in early AVN[39]
Electrical Stimulation	Promotes bone regeneration and vascularization	Pain relief and structural improvement in trials[40]
Core Decompression	Relieves intraosseous pressure and promotes revascularization	70% success rate in early-stage patients[43]

4.1 Pharmacological interventions

- **Bisphosphonates:** Bisphosphonates, such as alendronate, inhibit osteoclast-mediated bone resorption and have demonstrated efficacy in preventing femoral head collapse in early-stage AVN.[32] A randomized controlled trial showed a 40% reduction in collapse rates among patients treated with alendronate compared to placebo.[33]

- **Anticoagulants:** Anti-coagulants like enoxaparin address hypercoagulability associated with specific non-traumatic causes of AVN, such as thrombophilia and sickle cell disease.[34] By reducing vascular occlusion, these agents help restore blood flow and prevent further ischemia.[35]

- **Statins:** Statins, commonly used for hyperlipidemia, have shown potential in mitigating AVN progression by reducing bone marrow lipid deposition and improving microcirculation.[36] Experimental studies indicate that statins decrease femoral head necrosis incidence in steroid-induced AVN models.[37]

- **Other pharmacological agents:** Corticosteroid-sparing agents, such as iloprost, a prostacyclin analogue, have been investigated for their vasodilatory effects, which improve microvascular perfusion and reduce ischemic damage.[38]

4.2 Physical and Non-Pharmacological interventions

- **Physiotherapy:** Physiotherapy is integral to conservative management. It focuses on pain relief, strengthening periarticular muscles, and improving joint mobility. Low-impact exercises, such as swimming and cycling, are recommended to minimize stress on the femoral head.[39]

- **Electrical stimulation:** Electrical stimulation, including pulsed electromagnetic fields (PEMF), has shown promise in promoting bone regeneration and reducing pain by enhancing osteoblast activity and vascularization.[40]

- **Weight management:** Maintaining a healthy weight reduces mechanical stress on the affected joint, potentially slowing disease progression and improving functional outcomes.[41]

4.3 Core decompression without grafting

Core decompression involves drilling into the femoral head to reduce intraosseous pressure and promote revascularization. Although traditionally considered a surgical intervention, it can be performed without bone grafting as a minimally invasive conservative option in early-stage AVN.[42] Clinical studies report pain relief and delayed progression in up to 70% of patients undergoing this procedure.[43]

4.4 Efficacy and Limitations

While conservative management offers substantial benefits in early-stage AVN, its efficacy diminishes as the disease progresses. Studies reveal that approximately 40%–50% of patients with advanced AVN eventually require surgical intervention despite initial conservative treatment.[44] Furthermore, the long-term outcomes of these interventions remain poorly defined, necessitating further research to establish standardized protocols.[45]

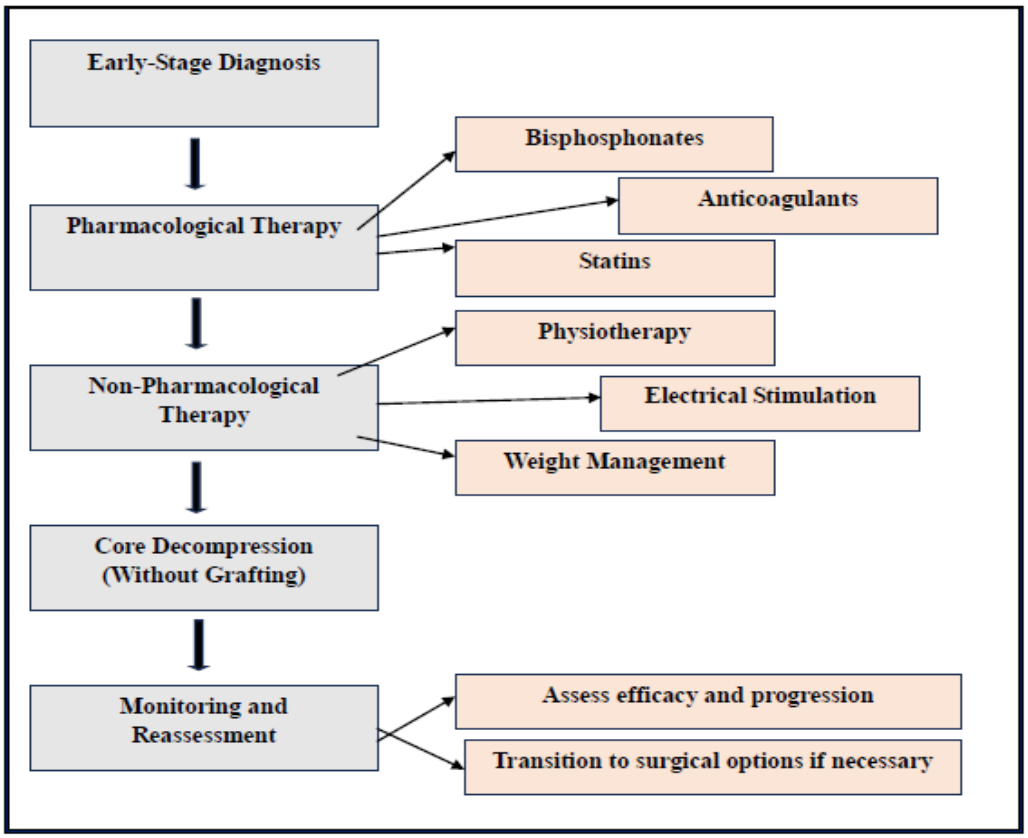

Figure 4: Flowchart: Conservative Management Pathway in AVN.

5. Surgical management of avascular necrosis

Surgical intervention is the cornerstone of management in advanced stages of avascular necrosis (AVN) when conservative treatments fail to halt disease progression or alleviate

symptoms. The goals of surgical management include pain relief, preservation of joint function, and prevention of further femoral head collapse.

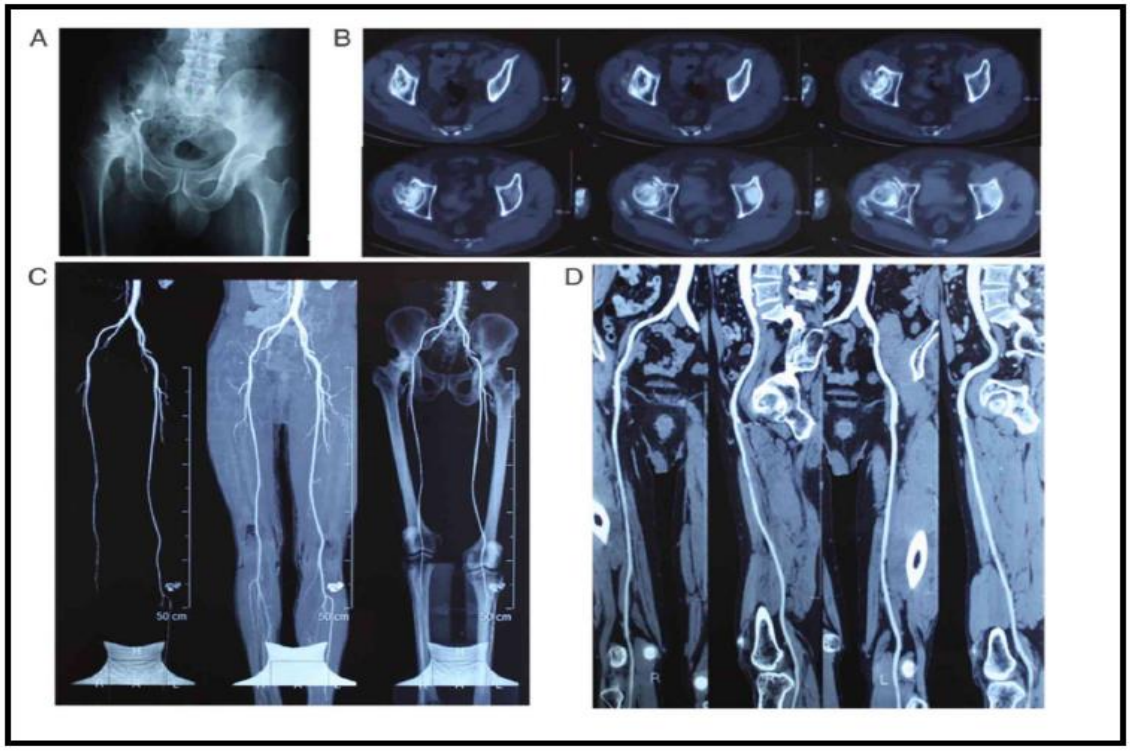

Figure 5: Non traumatic avascular necrosis of the femoral head.

Table 4: Summary of surgical management options.

Surgical technique	Indications	Outcomes
Core Decompression + Grafting	Early-stage AVN	60%–80% success in pain relief and joint preservation[47]
Osteotomy	Localized necrosis, minimal collapse	Delays need for THR by 10–15 years in 70% of cases[48]
Total Hip Replacement (THR)	End-stage AVN, secondary OA	90% achieve significant pain relief and function[50]
Resurfacing Arthroplasty	Younger patients, early-stage AVN	Bone stock preservation; variable long-term success[52]
Hemiarthroplasty	Older adults with isolated femoral head damage	Effective for limited functional demands[54]
Stem Cell Therapy	Adjunct to core decompression	Promising early results; long-term efficacy unclear[55]

5.1 Core decompression with bone grafting

Core decompression, a minimally invasive surgical procedure, involves drilling into the necrotic area of the femoral head to reduce intraosseous pressure and stimulate revascularization. In advanced cases, this technique is combined with bone grafting using

either autografts or allografts to enhance structural integrity and bone regeneration.[46] Studies have reported a 60%–80% success rate in early-stage AVN, with reduced pain and improved joint function.[47]

5.2 Osteotomy

Osteotomy involves reorienting the femoral head to shift weight-bearing forces away from the necrotic area, thereby preserving the joint. This technique is effective for patients with localized necrosis and minimal collapse. Long-term studies demonstrate that up to 70% of patients undergoing osteotomy avoid total hip replacement (THR) for 10–15 years.[48] However, the procedure is technically demanding and associated with a prolonged recovery period.[49]

5.3 Total Hip Replacement (THR)

THR is the definitive treatment for end-stage AVN characterized by extensive femoral head collapse and secondary osteoarthritis. The procedure involves replacing the damaged femoral head and acetabulum with prosthetic components. Modern advancements in implant materials and surgical techniques have improved outcomes, with over 90% of patients achieving significant pain relief and functional improvement.[50] However, complications such as prosthetic loosening, infection, and the need for revision surgery remain concerns, particularly in younger patients.[51]

5.4 Arthroplasty alternatives

- **Resurfacing arthroplasty:** Resurfacing arthroplasty involves capping the femoral head with a metal prosthesis while preserving bone stock. It is a preferred option for younger, active patients with early-stage AVN.[52] While this technique delays the need for THR, its long-term success is influenced by the extent of necrosis and patient compliance.[53]

- **Hemiarthroplasty**: In cases where only the femoral head is significantly affected, hemiarthroplasty replaces the femoral head while retaining the native acetabulum. This procedure is commonly performed in older adults with limited functional demands.[54]

5.5 Bone Marrow Concentrate and Stem Cell Therapy

Emerging techniques, such as bone marrow concentrate (BMC) injection and mesenchymal stem cell (MSC) therapy, are gaining traction as adjuncts to surgical interventions. These therapies aim to enhance revascularization and osteogenesis in necrotic bone. Clinical trials

have demonstrated promising results, with improved pain relief and delayed disease progression.[55] However, long-term efficacy and safety remain under investigation.[56]

Figure 4: Flowchart: Surgical Management Pathway for AVN.

Assessment of AVN Stage and Symptoms	
Early-Stage Interventions	Core Decompression + Bone Grafting
Intermediate-Stage Interventions	Osteotomy Resurfacing Arthroplasty
End-Stage Interventions	Total Hip Replacement (THR) Hemiarthroplasty
Adjunct Therapies	Bone Marrow Concentrate Injection Stem Cell Therapy
Post-Surgical Monitoring	Rehabilitation Evaluation for Complications

6. Comparative Analysis of Conservative and Surgical Management *(800–1000 words)*

The choice between conservative and surgical management for avascular necrosis (AVN) depends on factors such as the stage of the disease, extent of femoral head involvement, patient age, comorbidities, and functional demands. A comprehensive comparison highlights the advantages and limitations of each approach.

6.1 Efficacy across disease stages

Conservative management is most effective in early-stage AVN (Steinberg stages I and II), where preserving the femoral head and delaying progression are primary goals.[57] Pharmacological agents like bisphosphonates and anticoagulants, coupled with physiotherapy and electrical stimulation, have demonstrated a 50%–70% success rate in mitigating disease progression.[58] However, advanced stages (III and IV) with structural collapse and secondary arthritis typically require surgical intervention.[59] Total hip replacement (THR) remains the gold standard for end-stage AVN, offering over 90% symptom relief and functional improvement.[60]

6.2 Time to symptom relief

Conservative treatments often yield gradual improvement, requiring months of adherence to therapy. Conversely, surgical options, particularly THR, provide immediate pain relief and functional recovery in most cases.[61] However, surgical interventions entail longer rehabilitation periods and carry risks of complications such as infection and prosthetic failure.[62]

6.3 Durability and Long-Term Outcomes

The durability of outcomes significantly varies between the two approaches. Conservative management is less effective in preventing femoral head collapse in advanced stages, with up

to 50% of patients eventually requiring surgery.[63] Surgical interventions like osteotomy and THR have superior long-term outcomes, with THR implants lasting 15–20 years in most patients.[64]

6.4 Cost-Effectiveness

Cost considerations are vital in deciding between conservative and surgical options. Conservative treatments are generally less expensive initially but may require prolonged therapy, increasing cumulative costs.[65] Surgical options, while costlier upfront, are more cost-effective in advanced cases due to definitive symptom relief and reduced need for ongoing treatment.[66]

6.5 Patient-Centric Considerations

- **Age and Activity level:** Younger patients often prefer conservative or joint-preserving surgeries, such as core decompression or resurfacing arthroplasty, to delay THR.[67] Older patients with limited activity demand typically benefit more from definitive surgical interventions like hemiarthroplasty or THR.[68]

- **Comorbidities:** Patients with significant comorbidities, such as cardiovascular disease, may be unsuitable for surgery and are better managed conservatively.[69] Conversely, healthy patients can tolerate surgical options with lower complication risks.[70]

- **Quality of life:** Studies indicate that surgical interventions significantly improve quality-of-life metrics, including pain scores, mobility, and patient satisfaction, compared to conservative management in advanced cases.[71]

Table 5: Comparative Analysis of Conservative and Surgical Management.

Parameter	Conservative Management	Surgical Management
Indication	Early-stage AVN (Stages I and II)	Advanced AVN (Stages III and IV)
Time to Relief	Gradual, over months	Immediate, post-recovery period
Durability	Limited in advanced stages	Long-term, especially with THR[64]
Cost	Lower initial costs, higher cumulative costs	Higher upfront cost, cost-effective long-term
Quality of Life	Moderate improvement	Significant improvement in advanced cases[71]
Risks and Complications	Minimal side effects	Infection, prosthetic failure, revision surgery[62]

7. Outcomes and Prognosis

The outcomes and prognosis of avascular necrosis (AVN) of the femoral head vary widely based on the stage of the disease at diagnosis, the chosen management strategy, and patient-specific factors such as age, comorbidities, and adherence to therapy. This section provides a detailed overview of the clinical outcomes, factors influencing prognosis, and the long-term implications of AVN management.

7.1 Clinical outcomes

- **Conservative management:** In early-stage AVN, conservative treatments, including pharmacological agents, lifestyle modifications, and physiotherapy, are moderately effective in alleviating symptoms and delaying progression. Studies report pain relief and improved mobility in 50%–70% of patients treated conservatively during Steinberg stages I and II.[72] However, the efficacy diminishes as the disease progresses, with structural collapse of the femoral head occurring in up to 50% of cases despite treatment.[73]

- **Surgical management:** Surgical interventions generally yield superior outcomes compared to conservative approaches, particularly in advanced stages. Core decompression with bone grafting has shown success rates of 60%–80% in early-stage AVN, preventing collapse and preserving joint function.[74] Total hip replacement (THR), the gold standard for end-stage AVN, has a reported 90%–95% success rate in providing pain relief, restoring mobility, and enhancing quality of life.[75] Osteotomy and resurfacing arthroplasty also demonstrate favorable outcomes in selected patients, delaying the need for THR.[76]

7.2 Factors influencing prognosis

- **Disease stage:** Early detection and intervention are critical for improving outcomes. Patients diagnosed during early-stage AVN have a significantly better prognosis than those with advanced disease, where irreversible femoral head collapse has already occurred.[77]

- **Patient-Specific variables:** Age, comorbidities, and lifestyle choices such as smoking and alcohol consumption heavily influence prognosis. Younger patients with no significant comorbidities and good compliance to therapy demonstrate better long-term outcomes.[78]

- **Treatment modality:** The choice of treatment significantly affects prognosis. While conservative measures are effective for early-stage AVN, surgical interventions such as THR offer definitive relief in advanced cases, ensuring better long-term functional outcomes.[79]

7.3 Complications and Long-Term prognosis

- **Conservative management:** The primary limitation of conservative therapy is its inability to halt progression in advanced stages. Even with optimal adherence, many patients eventually require surgical intervention, underscoring the need for regular monitoring and timely escalation of care.[80]

- **Surgical management:** Surgical outcomes, particularly with THR, are generally excellent. However, long-term complications such as prosthetic loosening, dislocation, and infection remain concerns. Younger patients undergoing THR may require revision surgeries, especially if implants wear out within 15–20 years.[81]

- **Rehabilitation and Quality of Life:** Post-treatment rehabilitation plays a pivotal role in determining long-term prognosis. Physiotherapy, weight management, and lifestyle modifications enhance recovery and prevent complications. Studies have shown that comprehensive rehabilitation programs improve mobility, reduce pain scores, and enhance quality of life metrics in up to 85% of patients.[82]

Table 6: Summary of Outcomes and Prognosis in AVN Management.

Parameter	Conservative management	Surgical management
Efficacy	Moderate in early stages; limited in advanced stages	Excellent in advanced stages[75]
Disease progression	High risk of progression to collapse	Delays or prevents progression[74]
Pain relief	Gradual improvement	Immediate relief post-surgery[75]
Mobility	Moderate improvement	Significant restoration in advanced cases[76]
Complications	Disease progression despite treatment	Prosthetic failure, infection, revision surgery[81]
Long-Term prognosis	Variable; dependent on early detection	Excellent with successful surgical intervention[79]

8. Challenges and Future Directions in AVN Management

The management of avascular necrosis (AVN) remains complex, with several challenges limiting optimal outcomes despite advances in diagnosis and treatment. Addressing these

limitations while exploring innovative approaches is crucial for improving the prognosis and quality of life for affected individuals.

8.1 Challenges in AVN Management

- **Delayed diagnosis:** Early-stage AVN is often asymptomatic, leading to delays in diagnosis. Imaging modalities like MRI are highly sensitive but are not routinely utilized in patients with mild symptoms, causing many cases to progress to advanced stages before detection.[83]

- **Limited efficacy of conservative treatments:** Despite the availability of pharmacological and non-invasive interventions, their effectiveness in halting disease progression is limited, particularly in later stages. Factors like poor patient adherence, variability in response to therapies, and lack of standardized protocols exacerbate these limitations.[84]

- **Surgical complications:** Surgical interventions, though effective, are associated with potential risks. Complications like infection, implant failure, and need for revision surgeries affect a significant proportion of patients, particularly younger individuals undergoing total hip replacement (THR).[85]

- **Economic and Accessibility barriers:** The high cost of surgical procedures, particularly in low- and middle-income countries, limits access to definitive care. Additionally, disparities in healthcare infrastructure and availability of specialized surgeons further widen the treatment gap.[86]

- **Rehabilitation and Long-Term Compliance:** Many patients fail to adhere to post-treatment rehabilitation programs, which are critical for optimizing outcomes. Poor compliance leads to suboptimal recovery, recurrence of symptoms, and reduced quality of life.[87]

8.2 Future Directions in AVN Management

- **Advances in early diagnosis:** The development of biomarkers for early AVN detection holds promise for improving outcomes. Combining biomarkers with advanced imaging modalities such as dynamic contrast-enhanced MRI can facilitate early-stage diagnosis and intervention.[88]

- **Innovative pharmacological therapies:** Emerging therapies like gene editing, stem cell-based treatments, and novel drug delivery systems are being explored to enhance the efficacy of conservative management. Clinical trials involving mesenchymal stem cells have shown promising results in regenerating necrotic bone tissue.[89]

- **Minimally invasive surgical techniques:** The development of less invasive surgical approaches, such as percutaneous core decompression with biologic augmentation, is reducing recovery time and improving outcomes. These techniques are particularly beneficial for younger patients and those in early disease stages.[90]

- **Customizable Prosthetics and Smart Implants:** Advances in material science and biomechanics have led to the development of patient-specific prosthetics and smart implants. These innovations aim to reduce the risk of complications and enhance the longevity of surgical outcomes.[91]

- **Telemedicine and Digital health solutions:** Incorporating telemedicine into post-treatment care can improve patient adherence to rehabilitation programs. Mobile applications and wearable devices can monitor patient progress, provide reminders, and offer real-time feedback to healthcare providers.[92]

- **Policy and Healthcare reforms:** Strengthening healthcare policies to improve access to affordable AVN management is crucial. Public health initiatives focused on awareness, early screening, and subsidizing treatment costs can bridge the existing care gap.[93]

9. Conclusion

Avascular necrosis (AVN) of the femoral head is a debilitating condition with profound implications for patients' quality of life. Despite significant advancements in diagnostic and therapeutic modalities, the management of AVN remains challenging due to its multifactorial etiology, progressive nature, and variable treatment responses. This systematic review has highlighted the importance of early detection, stage-appropriate management, and the integration of emerging technologies to address gaps in care.

The pathophysiology of AVN involves complex interactions between vascular compromise, bone necrosis, and subsequent structural collapse, emphasizing the need for a multidisciplinary approach to its management. Conservative treatments such as

pharmacological interventions, lifestyle modifications, and physiotherapy are effective primarily in early-stage AVN but often fall short in preventing disease progression. Conversely, surgical options, including core decompression, osteotomy, and total hip replacement (THR), offer definitive solutions for advanced stages, albeit with associated risks and limitations.

Emerging therapeutic strategies such as stem cell therapy, gene editing, and minimally invasive surgical techniques are poised to revolutionize AVN management. These advancements, combined with early diagnostic tools like dynamic MRI and biomarkers, hold promise for improving outcomes by facilitating timely interventions. Moreover, personalized medicine, including patient-specific prosthetics and smart implants, represents the future of AVN care, offering tailored solutions for diverse patient needs.

The integration of digital health technologies, such as telemedicine and wearable devices, is pivotal in enhancing rehabilitation adherence and monitoring long-term outcomes. However, economic barriers and healthcare disparities remain significant challenges, particularly in resource-limited settings. Addressing these issues through policy reforms, public health initiatives, and global collaboration is critical to ensuring equitable access to advanced AVN care.

In conclusion, the management of AVN requires a holistic, patient-centered approach that combines current best practices with innovative therapies and technologies. Future research should focus on optimizing early detection methods, refining conservative and surgical treatments, and exploring cost-effective strategies to bridge healthcare gaps. By addressing these priorities, the burden of AVN can be significantly reduced, ultimately improving patient outcomes and quality of life.

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11. Conflict of interest

The authors confirm that there are no competing interests with any institutions, organizations, or products that may influence the findings or conclusions of this manuscript.

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