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REVIEW

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Osteonecrosis of the Femoral Head. Optimizing the Early-Stage Joint-Preserving Surgical Treatment?

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ABSTRACT

Osteonecrosis of the femoral head (ONFH) is a debilitating condition with various etiologies. Comprehension of the pathophysiology of the disease is limited, adding to the challenge of devising a clinically effective treatment strategy. High clinical suspicion and magnetic resonance imaging aid early diagnosis, leading to less invasive and more effective treatment.

Recent advancements in joint-preserving surgical treatment have led to improved outcomes, reduced pain, and a higher hip survival rate for early onset osteonecrosis of the femoral head compared with more invasive approaches such as total hip replacement. Core decompression is the gold standard procedure to relieve the ischemic area of the femoral head and is crucial in the early stage of osteonecrosis.

The addition of biologic regenerative agents to core decompression is auspicious as they can introduce new cells to the area of necrosis, osteoinductive and osteoconductive agents, while enhancing healing and cellular repair. Adjunctive bone marrow-derived cell therapies have been advocated, potentially aiding the regenerative process.

Arthroscopic core decompression and robot-assisted orthopaedic surgery are believed to improve the precision of graft placement, decreasing radiation and operative time.

The current study provides a comprehensive review and update of the literature surrounding the latest developments regarding joint-preserving surgical treatment for patients with osteonecrosis of the femoral head.

Keywords: osteonecrosis, core decompression, hip preservation, femoral head, avascular necrosis, bone-graft.

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INTRODUCTION

Osteonecrosis of the femoral head (ONFH) is a potentially devastating disease in the young population that can lead to hip joint destruction and, in the late stages, to total hip replacement (THR). Suspicion and early diagnosis of the pathology are crucial to obtain a favorable outcome. Osteonecrosis of the femoral head is a complicated pathophysiological process involving venous congestion and impaired blood supply interruption of the femoral head, causing cell death. Osteonecrosis of the femoral head is also known as avascular necrosis (AVNFH) or aseptic necrosis (ANFH) of the femoral head. The condition's etiology is unclear but is highly associated with traumatic or non-traumatic factors such as chronic steroid use, alcoholism, and other less common conditions. Osteonecrosis of the femoral head is challenging to diagnose on plain radiographs in the early stages of the disease. High suspicion should rise when a young patient presents with hip pain and negative X-rays (1-2). Magnetic resonance imaging is a sensitive and specific tool for an early diagnosis. In general, possible collapse and disease progression can be predicted by the size and location of the lesion. The Ficat and Arlet classification system is the most widely used (1-2). Non-operative treatment has been studied using bisphosphonates, anticoagulants, vasodilators, statins, and biophysical modalities (3). Joint preservation procedures were introduced to avoid or postpone the need for THR. Pre-collapse osteonecrosis with small, medially located lesions has been treated successfully by core decompression for decades and remains a viable option. A promising technique for introducing new cells to the area of necrosis is the addition of biologic regenerative agents to core decompression. These agents also promote healing and cellular repair *via* cytokine and growth-factor secretion. Core decompression with or without graft, surgical head-preserving procedures, stem cell augmentation, or biologic adjuncts have all been suggested with heterogeneous results and limited evidence to date (1-4). ❑

MATERIAL AND METHODS

Two reviewers conducted a systemic independent search of the literature on clinical trials from electronic databases, including MEDLINE/PubMed, Embase, Web of Science, and Cochrane Database of Systematic Reviews (CDSR). Further articles were also discovered from related references. The following search terms were used: hip, osteonecrosis, avascular necrosis, aseptic necrosis, core decompression, bone graft, and bone marrow. We also carried out cross-referencing and hand searches of short-listed studies' reference list to retrieve additional results.

In order to be included in the present review, the studies had to be conducted on patients with early-stage ONFH who underwent core decompression. Extracted data included authors, publication data, patients, age, gender, study location, diagnosis, and intervention.

Joint-preserving procedures

Core decompression

Core decompression (CD) is the most widely cited technique to reduce pain and prevent further joint deterioration in the early stages. Ficat and Arlet first described this technique during their attempt to obtain biopsy specimens to confirm the diagnosis in the pre-MRI era (5). The original CD was performed by tunneling an 8–10 mm trephine into the necrotic lesion. Core decompression's theoretical advantage is that it relieves pain by reducing venous congestion and bone-marrow pressure. The decrease in intraosseous pressure leads to increased blood flow towards the necrotic area, thus alleviating the pathologic process and promoting neovascularization (6, 18). Pre-collapsed stages of the disease with small – defined as less than 15% of the femoral head or Kerboul angle < 20° – medially located lesions predispose to a better outcome (7). Core decompression has been shown to have a significantly higher success rate than non-surgical management of early-stage disease. The technique of CD varies in terms of surgical approaches, the number of drillings, and trephine diameter. Experts recommend drilling multiple small holes to maximize the procedure's efficacy. This multiple drilling approach targets the lesion more easily. A small diameter drilling has been associated with minimal morbidity, less risk of weakening the femoral head and the articular cartilage, and less risk of stress risers that ultimately could lead to a subtrochanteric fracture (4, 8, 18). Some studies also conclude that

the CD of the femoral head releaves the painful symptomatology in the short term but does not appear to alter the progression of the bone lesion in the long term (9, 18). Review studies revealed that, despite the high heterogeneity amongst studies, CD alone achieved short-term clinical improvement in most cases. In a review study, results from 1134 hips, of which nearly 80% with early-stage osteonecrosis, showed that approximately 38% of patients underwent a THR at an average of 26 months following CD without augmentation (10). Strong evidence suggests that preoperative staging is an important factor affecting postoperative results. The success rate of CD at stage III osteonecrosis is only 27.44%. This procedure is significant since it can prevent or delay THR in young patients with early femoral head necrosis. Common surgical procedures improving core decompression are CD plus autologous bone marrow (CD + Marrow) and CD plus autologous bone (A.B) grafting (CD + A.B) (11, 23).

Biological enforcement of core decompression

Autologous bone graft, allograft, or synthetic bone substitute

The necrotic area can be filled using non-vascularized bone grafts from different sources (allograft, autograft, or artificial). The former necrotic area can be refilled with autologous bone, especially in the subchondral region, improving the osteogenic and osteoinductive capacity while avoiding a possible immune rejection. Even though underlying biochemical processes are not fully understood yet, a two-phase model has been proposed. Assumingly, the code consists of a disintegrating osteoclast-driven phase and a bone-rebuilding osteoblast-driven phase. Both phases are controlled by numerous growth factors and signaling molecules – bone morphogenetic proteins (BMP), tumor necrosis factor (TNF), and osteoprotegerin (OPG) – which balance the course of bone resorption and bone formation (17). The success rate of CD can be significantly improved by using bone marrow or autologous bone (8). In a review study, CD + Marrow had a success rate of 74%, while CD+A.B had a success rate of 81%, both being higher than the overall success rate of 65%. CD+A.B and CD + Marrow significantly reduced the conversion rate to THR compared to CD on its own (11). However, its disadvantages include increased patient trauma area, insufficient bone supply, prolonged operation time, and many complications in the donor site (12).

The femoral head CD combined with synthetic calcium-sulfate bone grafting is a viable option, bearing a low risk of femoral head collapse. In osteogenesis, calcium sulfate hemihydrate powder forms a solid precipitate through an agglutination reaction after hydration. Hence, a stable environment for the growth of new bone or solid mechanical support for regional grafting can be established by the bone conduction of calcium sulfate hemihydrate powder, bearing a portion of stress conduction (20). Also, bone substitute is an option to avoid donor site complications. Advanced core decompression (ACD), a relatively new technique, uses a percutaneous expandable reamer that allows more efficient removal of necrotic tissue. The use of synthetic bone substitute composed of calcium sulfate ($CaSO_4$)/calcium phosphate ($CaPO_4$) in conventional ACD and a mixture of autologous cancellous bone from the femoral neck and the exact synthetic bone substitute can be used in cases of modified advanced CD (17, 21). A distinct age-dependent rate of hip survival was observed for ONFH patients treated with ACD. Treatment in patients aged over 40 has a higher rate of failure. Patients' sex does not seem to affect treatment outcomes (17). Patients treated with the previous ACD treatment without autologous bone showed a hip survival rate of 67%, similar to the survival rate of 65% reported for conventional CD. Overall success rates of 75.9% after a mean follow-up of 30.06 months have been seen for the modified ACD technique (ACD technique with autologous bone). A modification of ACD uses autologous bone refilling of the former necrotic area, especially in the subchondral region. For refilling the remaining drilling canal, a synthetic bone graft may be helpful, as it results in good bone remodeling when in contact with healthy bone, ensuring the stability of the femoral bone after ACD treatment, equal to that on the untreated opposite side (21).

Autologous bone has been proven superior in biomechanical properties compared to all other types of bone grafts. The impaction of autologous bone derived from the femoral neck into the necrotic defect has been evaluated. Autologous bone has better biological properties as it is osteoconductive, osteoinductive, and osteoge-

nic (21-23). Kong *et al* studied the outcome of percutaneous CD with bone grafting on ONFH, and they concluded that this method could be used to treat the early stage of ONFH effectively. This treatment can significantly relieve symptoms, improve hip movement, and postpone or stop femoral head collapse (24). Also, harvesting the autologous bone graft from the femoral neck during CD may be used to avoid donor site complications. The outcome is influenced by the femoral head's initial and the remaining necrotic volume. Similar to the described technique of femoral neck graft harvesting, debridement of the core can be achieved by using a bigger-size reamer or a more aggressive and corresponding size of bone graft harvest trephine with a diameter of 7.0 mm to 10.0 mm (22). Guiding the trephine using a guide wire makes the femoral neck autologous bone harvest sufficient and straightforward. By harvesting adequate quantities of bone from the femoral neck, it is attainable to avoid the additional bone harvest from the iliac crest, which increases the risk of morbidity. In most early and midterm cases, harvesting autograft from the femoral neck adds an advantage to CD's minimally invasive and joint preserving technique (21, 22).

Mesenchymal stem cells, growth-factor-based treatment, or bone-marrow implantation

There is considerable enthusiasm regarding biological therapies which can enhance CD with osteogenic (mesenchymal stem cells) and osteoinductive agents (bone morphogenic protein) (18). ONFH is characterized by compromised vascular supply, necrosis, and subsequent microfracturing without adequate bone remodeling and healing (7, 18). A decrease in the levels of osteoprogenitor cells in hematopoietic and stromal marrow compartments has been exhibited in this disease (19). The deficiency of osteoprogenitor cells compromises the healing and remodeling abilities of the bone (8, 18). Cell therapy, such as mesenchymal stem cell (MSC) transplantation or bone marrow aspirate concentrate injection, has demonstrated benefits such as pain relief, reduced time to collapse, decreased lesion size, and functional restoration in previously published reports (25, 26). Depending on the source of the tissue, MSCs are named bone marrow-derived MSCs (BMSCs), adipose-derived MSCs (AMSCs), peripheral blood-derived MSCs (PBMSCs), and umbilical cord-derived mesenchymal stem cells (UCMSCs). Systematic reviews found that implantation of BMSCs into the CD track was more efficacious in treating ONFH than CD treated alone. Additionally, it was associated with delayed ONFH progression, reducing the necrotic area of the femoral head, decreasing the need for THR, and improving Harris's hip score (27-29, 32).

The objective of adding MSCs into the CD tunnel is to supply osteoprogenitor and vascular progenitor cells to the area of decompressed necrotic bone, facilitating tissue regeneration and repair. Among the various types of mesenchymal stem cells, bone marrow-derived mesenchymal stem cells (BM-MSCs) are most commonly used owing to their superiority in cartilage and bone repair. Moreover, BM-MSCs can release exosomes containing cytokines that promote angiogenesis, osteogenesis, and chondrogenesis, including vascular endothelial growth factor, transforming growth factor-beta, and bone morphogenetic protein-2 (8, 25). Since 2002, after Hernigou *et al* (19) first described a technique for mesenchymal stem cell injection into an area of necrosis, four studies have prospectively evaluated the use of stem cells and CD. Direct instillation through the core tract is the most commonly performed procedure (18). In a systematic review by Papakostidis *et al* and a meta-analysis of seven studies examining the efficacy of BMSC in addition to CD in ONFH, the results indicated that CD with autologous BMSCs was superior to CD alone regarding the structural failure of the femoral head (OR = 0.2, 95% CI 0.08–0.60, p = 0.02) (13). Additionally, in a meta-analysis seven trials, Yuan *et al* evaluated the clinical outcomes of BMSC implantation in cases of ONFH. A delayed progression of osteonecrosis (OR = 0.17, 95% CI 0.09–0.32, $p < 0.001$) as well as a lower incidence of THR were noted in the BMSC group compared to control groups (OR = 0.30, 95% CI 0.12–0.72, $p < 0.01$) (32). No significant heterogeneity was found amongst the included studies, while further sensitivity analysis did not reveal any statistical differences when different studies were excluded (14). Despite the encouraging results, inconsistencies due to the heterogeneity of the presented cases in terms of disease stage, etiology, and lesion size were observed in the literature (4). Many unsolved problems and challenges, including pa-

tient selection and standardized procedures, remain in practical application. Therefore, more studies are required to find the ideal cell sources, appropriate transplantation methods, and optimal number of cells for transplantation (29).

Bone morphogenetic protein (BMP) has been deployed as an addition to CD due to the ability of the biological molecule to promote osteogenesis. The bone matrix is rich in BMP, inducing osteogenesis in normal bone tissue and generating bone and cartilage tissue in surrounding soft and bone tissues (11). Lieberman *et al* published a case series of 15 patients (17 hips) treated with CD, fibular allograft, and human BMP (50 mg) for femoral head osteonecrosis. All 17 hips included in the retrospective study were in the early pre-collapsed stage, with three out of 17 showing disease progression with subsequent conversion to THR after follow-up (15, 33). In a report published by Sun *et al*, the impact of bone graft versus impacted bone graft with recombinant BMP (BMP-2) treatment on patients' clinical outcome was compared. However, the results showed no statistical difference between the study arms (16, 34). Exogenous BMP positively affects the treatment of femoral head necrosis by promoting femoral head repair, curing, or delaying disease progression (11).

Platelet rich plasma (PRP) could augment CD and bone graft substitutes to treat early-stage ONFH by increasing the levels of cytokines that initiate and regulate proliferation, differentiation, and angiogenesis. The cytokines identified in PRP include transforming growth factor-β (TGF-β), platelet-derived growth factor (PDGF), insulin-like growth factor (IGF), basic fibroblast growth factor (bFGF), endothelial growth factor (EGF), and vascular endothelial growth factor (VEGF). Isolated PRP treatment will not be effective on ONFH. Platelet rich plasma can be used in combination with stem cells and growth factors such as PDGF, TGF-β, basic fibroblast growth factor (bFGF), vascular endothelial growth factor (VEGF), and endothelial growth factor (EGF). These significantly affect the proliferation and differentiation of mesenchymal stem cells (MSCs) and tissue repair. Platelet rich plasma is recommended as adjunctive therapy for CD combined with stem cells and bone grafts (autologous or allogeneic) to induce osteogenic activity, stimulate the differentiation of stem cells in ARCO stage I and II patients, induce angiogenesis to accelerate bone healing, inhibit inflammatory reactions in necrotic lesions, and prevent apoptosis induced by glucocorticoids (30, 31). The most efficient combination of cell therapy associated with CD is still to be evaluated.

Optimizing the accuracy of core decompression

Assisted endoscopic, arthroscopic, navigated, or robotic core decompression

The necrotic volume of the femoral head influences the outcome, as accurate decompression indicates treatment success (34). Core decompression aims to scrape the lesion to the peripheral wall of the bone, which is close to normal bone tissue, thus improving blood circulation of the bone bed and facilitating the growth of the blood vessels along the CD tunnel into the femoral head and promoting femoral head repair. The conventional free-hand fluoroscopy technique uses intraoperative visualization *via* an image intensifier. It can be performed in only one plane at a time and requires complex hand-eye coordination. Endoscopic evaluation of the removed necrotic bone can significantly improve the therapeutic effect by visualizing the borders of the decompressed bone area and providing information regarding the necessity for bone graft and the type of graft required (37). It is possible to increase the treatment efficacy of the ONFH when appropriate additional treatments are applied based on endoscopic findings during the decompression procedures in pre-collapse ONFH (38).

Arthroscopic management of ONFH bears the advantage of being both diagnostic and therapeutic (33). Arthroscopic examination of the hip joint includes femoral head assessment for suspected collapse, observation of the articular cartilage overlying the acetabulum, probing the articular cartilage to identify any softening or chondral flaps, and inspection of the chondrolabral junction. Also, arthroscopy's visualization ensures no perforation of the cortical bone, articular cartilage, or joint space by either the guide pin or the reamer. Unlike percutaneous standard CD, arthroscopic-assisted CD allows for the arthroscopic treatment of concomitant intra-articular pathology associated with ONFH, including loose bodies, pincer lesions, cam lesions, synovitis, labral tears, and chondral defects. Interestingly, the effect of irrigation pressure, trac-

tion, and osteoplasty terminal circulation of the femoral head is unknown (33, 36).

Accuracy is essential during core decompression. Nevertheless, conventional 2D imaging techniques such as X-ray, CT, and MRI make it challenging to precisely locate the irregular ischemic areas. As a result, multiple drillings and depths are often necessary, increasing radiation exposure for both the surgical team and patient. Moreover, it can increase the risk of iatrogenic cartilage and bone fracture. Multiple drilling also means more extended surgical time, thus greater risk for subsequent infection and other surgical complications. Computer-assisted imaging is utilized to increase surgical accuracy. These new techniques enable computer-assisted orthopaedic surgery (CAOS). Computed tomography and MRI scan data provide much higher precision than conventional techniques. Some types of CAOS provide simultaneously coronal and sagittal plane views on the system-associated screen during surgery. These systems promise a high accuracy and reduction of radiation exposure time, but the lengthy registration process still limits it. Moreover, the inevitable steep learning curve and device expenses hamper the implementation of these navigational systems in less developed areas (34, 36).

Robot-assisted orthopaedic surgery may improve the precision of implant placement and decrease radiation and operative time. TiRobot™ is an orthopaedic surgery robot that can implant different guidewires and screws and can be used for guidewire insertion to the proximal femur and spine. TiRobot™ was created to combine navigation and robot techniques using an intraoperative C-arm, enabling accurate positioning, adequate steadiness, and repeatability. It can decrease intraoperative radiation exposure and reduce the operation time compared to conventional free-hand surgery (35). ❑

CONCLUSION

Joint-preserving procedures are vital for the survival of the femoral head when treating osteonecrosis at the early stages of the disease. Core decompression is the gold standard procedure to relieve the ischemic area of the femoral head. Endoscopic assisted procedures secure the effectiveness of the core decompression, leading to a vital bone capable of healing and reform. The subchondral ischemic area must be supported by structural bone autograft, harvested from the femoral neck, and filled in the removed necrotic area favoring the minimal invasive characteristics of the procedure. The pathological area and the bone autograft must always be enforced to heal, assisted by cell therapies such as bone marrow-derived mesenchymal cells and platelet-rich plasma. The ideal combination of therapies resulting in the best outcome still has to be studied and proved. ❑

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References

1. **Larson E, Jones LC, Goodman SB, et al.** Early-stage osteonecrosis of the femoral head: where are we and where are we going in year 2018? *Int Orthop* 2018;42:1723-1728.
2. **Charalampos G Zalavras, Jay R Lieberman.** Osteonecrosis of the femoral head: evaluation and treatment. *J Am Acad Orthop Surg* 2014;22:455-464.
3. **Anna Cohen-Rosenblum, Quanjun Cui.** Osteonecrosis of the Femoral Head. *Orthop Clin North Am* 2019;50:139-149.
4. **Atilla B, Bakırcıoğlu S, Shope AJ, Parvızı J.** Joint-preserving procedures for osteonecrosis of the femoral head. *EFORT Open Rev* 2019;4:647-658.
5. **Ficat RP.** Idiopathic bone necrosis of the femoral head. Early diagnosis and treatment. *J Bone Joint Surg Br* 1985;67:3-9.
6. **Johnson AJ, Mont MA, Tsao AK, Jones LC.** Treatment of femoral head osteonecrosis in the United States: 16-year analysis of the Nationwide Inpatient Sample. *Clin Orthop Relat Res* 2014;472:617-623.
7. **Calori GM, Mazza E, Colombo A, et al.** Core decompression and biotechnologies in the treatment of avascular necrosis of the femoral head. *EFORT Open Rev* 2017;2:41-50.
8. Microsurgery Department of the Orthopedics Branch of the Chinese Medical Doctor Association; Group from the Osteonecrosis and Bone Defect Branch of the Chinese Association of

Reparative and Reconstructive Surgery; Chinese Guideline for the Diagnosis and Treatment of Osteonecrosis of the Femoral Head in Adults. Microsurgery and Reconstructive Surgery Group of the Orthopedics Branch of the Chinese Medical Association.
Orthop Surg 2017;9:3-12.

9. **de Souza Miyahara H, Rosa BB, Hirata FY, et al.** What is the role of core decompression in the early stages of osteonecrosis of the femoral head? Evaluation of the surgical result by functional score and radiological follow-up.
Rev Bras Ortop 2018;53:537-542.
10. **Andronic O, Weiss O, Shoman H, et al.** What are the outcomes of core decompression without augmentation in patients with nontraumatic osteonecrosis of the femoral head?
International Orthopaedics 2021;45:605-613.
11. **Hua K-C, Yang X-G, Feng J-T, et al.** The efficacy and safety of core decompression for the treatment of femoral head necrosis: a systematic review and meta-analysis.
J Orthop Surg Res 2019;14:306.
12. **Ignjatovic N, Ninkov P, Ajdukovic Z, et al.** Biphasic calcium phosphate coated with poly-d,l-lactide-co-glycolide biomaterial as a bone substitute.
J Eur Ceram Soc 2007;27:1589-1594.
13. **Papakostidis C, Tosounidis TH, Jones E,** Giannoudis PV. The role of 'cell therapy' in osteonecrosis of the femoral head: a systematic review of the literature and meta-analysis of 7 studies.
Acta Orthop 2016;87:72-78.
14. **Yuan HF, Zhang J, Guo CA, Yan ZQ.** Clinical outcomes of osteonecrosis of the femoral head after autologous bone marrow stem cell implantation: a meta-analysis of seven case-control studies.
Clinics (Sao Paulo) 2016;71:110-113.
15. **Lieberman JR, Conduah A, Urist MR.** Treatment of osteonecrosis of the femoral head with core decompression and human bone morphogenetic protein.
Clin Orthop Relat Res 2004;429:139-145.
16. **Sun W, Li Z, Gao F, et al.** Recombinant human bone morphogenetic protein-2 in debridement and impacted bone graft for the treatment of femoral head osteonecrosis.
PLoS One 2014;9:e100424.
17. **Serong S, Haversath M, Tassemeier T, et al.** Results of advanced core decompression in patients with osteonecrosis of the femoral head depending on age and sex—a prospective cohort study.
J Orthop Surg Res 2020;15:124.
18. **Moya-Angeler J, Gianakos AL, Villa JC, et al.** Current concepts on osteonecrosis of the femoral head.
World J Orthop 2015;6:590-601.
19. **Hernigou P, Poignard A, Zilber S, Rouard H.** Cell therapy of hip osteonecrosis with autologous bone marrow grafting.
Indian J Orthop 2009;43:40-45.
20. **Zhao P, Hao J.** Analysis of the long-term efficacy of core decompression with synthetic calcium-sulfate bone grafting on non-traumatic osteonecrosis of the femoral head.
Med Sci (Paris) 2018;34 Focus issue F1:43-46.
21. **Landgraeber S, Warwas S, Claßen T, Jäger M.** Modifications to advanced Core decompression for treatment of Avascular necrosis of the femoral head.
BMC Musculoskeletal Disorders 2017;18:479.
22. **Karampinas PK, Zafeiris CP, Vlamis JA.** Femoral neck bone autograft for the core decompression treatment of the hip osteonecrosis: Surgical technique.
WJARR 2021;10:196-202.
23. **Lin L, Jiao Y, Luo X-G, et al.** Modified technique of advanced core decompression for treatment of femoral head osteonecrosis.
World J Clin Cases 2020;8:2749-2757.
24. **Kong FG, Han SH, Liu FW, Li YJ.** Percutaneous core decompression combined with percutaneous coronary intervention for the treatment of femoral head necrosis in adults.
Zhongguo Yiyao Zhinan 2014;35:32-34.
25. **Li M, Ma Y, Fu G, et al.** 10-year follow-up results of the prospective, double-blinded, randomized, controlled study on autologous bone marrow buffy coat grafting combined with core decompression in patients with avascular necrosis of the femoral head.
Stem Cell Res Ther 2020;11:287.
26. **Talathi NS, Kamath AF.** Autologous stem cell implantation with core decompression for avascular necrosis of the femoral head.
J Clin Orthop Trauma 2018;9:349-352.
27. **Xu S, Zhang L, Jin H, et al.** Autologous Stem Cells Combined Core Decompression for Treatment of Avascular Necrosis of the Femoral Head: A Systematic Meta-Analysis.
Biomed Res Int 2017;2017:6136205.
28. **Wang S-L, Hu Y-B, Chen H, et al.** Efficacy of bone marrow stem cells combined with core decompression in the treatment of osteonecrosis of the femoral head A PRISMA-compliant meta-analysis.
Medicine 2020;99:25.
29. **Xu Y, Jiang Y, Xi CS, et al.** Stem cell therapy for osteonecrosis of femoral head: Opportunities and challenges.
Regenerative Therapy 2020;15:295e304.
30. **Han J, Gao F, Li Y, et al.** The Use of Platelet-Rich Plasma for the Treatment of Osteonecrosis of the Femoral Head: A Systematic Review.
Biomed Res Int 2020;2020:2642439.
31. **D'Ambrosi R, Biancardi E, Massari G, et al.** Survival Analysis after Core Decompression in Association with Platelet-Rich Plasma, Mesenchymal Stem Cells, and Synthetic Bone Graft in Patients with Osteonecrosis of the Femoral Head.
Joints 2018;6:16-22.
32. **Wang Z, Sun Q-M, Zhang F-Q, et al.** Core decompression combined with autologous bone marrow stem cells versus core decompression alone for patients with osteonecrosis of the femoral head: A meta-analysis.
Int J Surg 2019 Sep;69:23-31.
33. **Nazal MR, Parsa A, Martin SD.** Mid-term outcomes of arthroscopic-assisted Core decompression of Precollapse osteonecrosis of femoral head – minimum of 5 year follow-up.
BMC Musculoskeletal Disorders 2019;20:448.
34. **Wang W, Hu W, Yang P, et al.** Patient-specific core decompression surgery for early-stage ischemic necrosis of the femoral head.
PLoS ONE 2017;12:e0175366.
35. **Bi B, Zhang S, Zhao Y.** The effect of robot-navigation-assisted core decompression on early stage osteonecrosis of the femoral head.
J Orthop Surg Res 2019;14:375.
36. **Theopold J, Armonies S, Pieroh P, et al.** Nontraumatic avascular necrosis of the femoral head: Arthroscopic and navigation-supported core decompression.
Oper Orthop Traumatol 2020;32:107-115.
37. **Vlamis J, Karampinas P, Kavroudakis E, Pneumaticos S.** The use of core track endoscopy to document accurate decompression of the femoral head.
Hip Int 2014;24:284-289.
38. **Pak H, Ri SG, Jang MG, Kim SJ.** Endoscopic observation finding in the core decompression procedure of osteonecrosis of femoral head and effect of additional treatments.
Int Orthop 2021;45:95-99.