Review Article

Advancements and Considerations in Ceramic Bearings for Total Hip Arthroplasty: A Narrative Review

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ABSTRACT

Objective

Total hip arthroplasty (THA) is a widely successful orthopedic procedure offering relief to patients suffering from hip joint disorders. Ceramic bearings, particularly ceramic-on-ceramic (CoC) surfaces, have gained attention for their remarkable tribological properties and biocompatibility. This article discusses the role of ceramic bearings in THA, including their historical background, stability, and potential complications. It explores the advantages of CoC bearings, such as their low wear rates and reduced risk of complications like aseptic loosening and prosthetic joint infections and delves into considerations like ceramic fracture and squeaking phenomena.

Materials and methods

This article is based on a rigorous literature search conducted across reputable academic databases, including PubMed, Scopus, Web of Science, and Google Scholar, the succeeding search keywords were applied: "total hip arthroplasty", "ceramic-on-ceramic", "total hip arthroplasty dislocation", "prosthetic joint infections", "ceramic fractures", "aseptic loosening", "squeaking".

Conclusion

Ceramic-on-Ceramic (CoC) bearings, while promising, are not commonly used in primary hip arthroplasty due to cost concerns and surgical precision requirements. However, they are gaining ground for younger, active patients.

Technological advancements have reduced the risks of implant fracture. Additionally, noise generation is not associated with an increase incomplication Nevertheless, patients should be informed about these rare risks during the preoperative consent process.

Keyword

total hip replacement, ceramic-on-ceramic bearings, aseptic loosening, squeaking, ceramic fracture.

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INTRODUCTION

Total hip arthroplasty (THA), a surgical orthopedic intervention, stands as a paragon of success and cost-efficiency within the medical sphere[1]. This well-established procedure consistently affords substantial advantages to individuals afflicted with advanced degenerative hip osteoarthritis (OA). It bestows respite from debilitating pain, reinstates functional prowess, and elevates the overall quality of life for the patient.

Hip OA represents the foremost indication for THA, with an annual prevalence of roughly 88 symptomatic cases per 100,000 patients in the United States. However, THA's utility extends beyond this singular domain. It also proves indispensable for addressing a spectrum of conditions, including inflammatory arthritis, congenital hip abnormalities, and hip osteonecrosis (ON). These varied conditions present unique clinical profiles and demand meticulous surgical considerations [2].

Among the various bearing surfaces utilized in total hip arthroplasty (THA), the predominant choice is metal-on-polyethylene (MoP), representing a prevalence of 51%. Following closely is the employment of metal-on-metal (MoM) configurations, which account for 35% of THA cases. In contrast, the application of ceramic-on-ceramic (CoC) bearing surfaces is less frequent, comprising only 14% of total THA procedures [3].

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A significant limitation associated with the metal-on-polyethylene (MoP) bearing surface is the occurrence of polyethylene wear particle generation. This phenomenon has been causally linked to the onset of periprosthetic inflammatory responses and osteolysis. This sequence of events can culminate in the ultimate malfunction and failure of the implanted prosthesis, as substantiated by previous investigations [4–8].

Likewise, patients with metal-on-metal (MoM) articulations have displayed increased serum concentrations of metal ions. These escalated metal ion levels are frequently associated with the potential manifestation of adverse repercussions, such as chromosomal anomalies and renal toxicity. [9–14] .

Additionally, the reappearance of corrosion problems in total hip arthroplasties employing metal-on-polyethylene (MoP) and metal-on-metal (MoM) designs with larger femoral heads is a source of significant concern [15–17]. These corrosion and wear byproducts have the potential to induce adverse tissue responses [17–19].

In contrast, ceramics, including inlays and heads, show favorable medium to long-term outcomes. Their exceptional tribological properties make them valuable alternatives to MoP or MoM combinations, especially for younger patients undergoing hip replacements [20–24].

Considering these advantages, the utilization of ceramic-on-ceramic hip prostheses is expected to rise significantly in the coming years [21].

METHODS AND MATERIALS

This review is based on a rigorous literature search for relevant studies on ceramic-on-ceramic (CoC) bearing surfaces in total hip replacement conducted across reputable academic databases, including PubMed, Scopus, Web of Science, and Google Scholar. The search criteria were defined to encompass a substantial historical scope, spanning the last 43 years (from January 1, 1980, to September 30, 2023), in order to comprehensively evaluate the evolution of research and advancements in the field, only English-language studies were considered. The search used a combination of keywords, including (ceramic-on-ceramic), (wear rates), (stability), (prosthetic joint infections), (aseptic loosening), (ceramic fractures), (squeaking), (hip dislocation) and (total hip replacement).

In addition to electronic database searches, manual searches were conducted to identify historic papers and earlier studies that might not be available electronically but were deemed valuable for this comprehensive review.

Historic Background

Ceramic bearings in the context of THA can be classified into two distinct types: Alumina and Zirconia. Notably, in 1970, Boutin pioneered the development of alumina (Al_2O_3) ceramics for bearing applications, marking a significant milestone despite the material's broader potential utility [25].

Alumina ceramics initially showed exceptional durability and sliding properties, confirmed through implant evaluations and hip simulator tests. However, inherent limitations arose, primarily in the form of fracture risks and the complexities associated with achieving stability when coupling ceramic femoral heads with metal stems [26].

Of note, the renowned commercial brand name associated with aluminum ceramics is BIOLOX® (CeramTec GmbH, Plochingen, Germany), widely acknowledged as an indispensable ceramic for implementation in THA [27].

Over the past four decades, three distinct generations of Biolox® ceramics have been progressively developed. These include Biolox®, introduced first, followed by Biolox®forte in 1995, and subsequently Biolox®delta in 2003. Each successive generation is generally presumed to exhibit improvements over its predecessor, particularly in terms of grain size, purity, and density [28].

This technology has undergone rigorous in vitro testing and extensive clinical evaluation before its widespread application. To date, more than 11 million Biolox® bearings (CeramTec GmbH, Plochingen, Germany) have been successfully implanted.

In comparison to aluminum, zirconia emerges as a superior choice for THA applications due to its notable toughness, outstanding mechanical properties, relatively lower wear rates, and exceptional resistance to breakage [29,30].

Biocompatibility, tribological performance, and mechanical attributes

In the assessment of total hip arthroplasty (THA) bearing surfaces, pivotal factors encompass biocompatibility, tribological characteristics, and mechanical performance. Ceramic-on-ceramic (CoC) surfaces are renowned for their exceptionally low wear rates [31–33].

Among different bearing surfaces, ceramic-on-ceramic (CoC) exhibits the lowest wear rate, with less than 0.001 mm per year. In contrast, metal-on-conventional polyethylene has a wear rate of 0.137 mm per year, while ceramic-on-conventional polyethylene shows 0.072 mm per year. Metal-on-highly cross-linked polyethylene has a wear rate of 0.042 mm per year, and ceramic-on-highly cross-linked polyethylene demonstrates 0.030 mm per year. Metal-on-metal also maintains a low wear rate, with 0.005 mm per year [31–34].

This exceptional resistance to wear renders CoC bearings an optimal choice, particularly for younger and more active patients. The inherent hydrophilic nature of ceramic surfaces further contributes to reduced friction between moving components, ensuring effective lubrication [35,36].

Furthermore, ceramic bearings are deemed safe owing to their low release of metal ions and the exceptional biocompatibility of wear particles. Notably, no documented instances have linked pseudotumors or systemic reactions to wear particles originating from Ceramic-on-Ceramic (CoC) bearings [37,38].

Hernigou *et al.*'s study supports alumina-alumina (Al-Al) bearings over polyethylene in reducing wear and osteolysis. In a 20-year study with bilateral arthroplasties, patients with CoC bearings experienced no hip loosening or revisions.

Osteolysis assessment, using X-rays and CT scans, consistently showed less osteolysis in CoC hips. Comparing CoP and CoC hips within patients favored CoC-bearing hips, with significantly smaller osteolysis volumes. CoC bearings have the potential to nearly eliminate radiographic osteolysis. is [39].

Additionally, several arthroplasty registries worldwide have reported a favorable association between the utilization of ceramic heads and reduced revision rates in comparison to their metallic counterparts [40–44], Implants that incorporated traditional polyethylene exhibited poorer outcomes concerning implant longevity, hip functionality, and rates of wear. In contrast, implants that included traditional polyethylene showed inferior performance in terms of implant longevity, hip function, and wear rates [45].

In conclusion, while hypersensitivities and metallosis are rare, ceramic heads are particularly indicated in cases where cobalt-chromium (CoCr) heads may jeopardize patient health, especially among individuals known to have metal hypersensitivity, impaired renal functions, or other relevant comorbidities.

Stability and Dislocations

Dislocation remains a prominent cause of revisions following primary THA procedures [46]. At present, approximately 8% to 12% of annual hip surgeries are revision surgeries, with a notable 11% to 24% of these revisions addressing THA dislocations [47].

In a study conducted by Woo and Morrey involving 10,500 patients, a dislocation rate of 3.2% was reported. It is worth noting that nearly half of all dislocations occur within the initial 3 months post-surgery, and more than three-quarters take place within the first year [48].

Patients who have previously experienced one dislocation are at an increased risk of subsequent dislocations. Enhanced joint stability can be attributed to greater excursion distance and range of motion before dislocation, particularly when larger-diameter femoral heads are used [49].

CoC bearings enable the use of larger femoral heads while maintaining the dimensions of the acetabular component. This is primarily due to the reduced material thickness requirement and serves as the main rationale for their preference over other options [38,50].

In contrast to polyethylene bearings, several studies have demonstrated lower risks of late dislocations when CoC bearings are employed [51].

Ceramic-on-Ceramic and prosthetic joint infections (PJI)

Lenguerrand *et al.* examined numerous risk factors and their connections to PJI revision surgery. They analyzed patient-related factors like age and gender, health system-related factors such as surgical facility location and caseload, and surgery-related factors including osteoarthritis and femoral neck fractures. The study also explored various joint arthroplasty bearings and their impact on PJI occurrence. Importantly, ceramic bearings were found to be associated with a lower likelihood of PJI revision compared to metallic bearings [52].

An analysis of the Australian register conducted by Madanat *et al.* showed a higher rate of revision related to infections in both MoP and CoP hips when compared to CoC. The use of ceramic bearings led to a significantly reduced incidence of infection revision for patients younger than 70. These differences were observed regardless of the type of prosthesis used [53].

Aseptic Loosening

The concept of aseptic loosening involves debris wearing [54], and investigations conducted on hip simulators indicated a reduction in wear rates while using CoC bearings as against the MoP variants.

A hip simulator research showed an alumina liner wear rate of 0.004 mm^3 in every million cycles for over 14 million cycles in steady-state for the combinations of alumina head-alumina cup. In contrast, the values observed when using polyethylene liners, as with MoP bearing, was 13 mm^3 in every million cycles [55].

According to Stewart *et al.* (2001), hip simulator investigations previously performed under extreme micro separation circumstances showed a value of 1.3 mm^3 in every million cycles while using the BIOLOX forte. Conversely, the value observed while using the BIOLOX delta component was 0.12 mm^3 in every million cycles [56].

It was reported that the retrieved CoC bearings of BIOLOX forte had a mean wear rate of 0.5 and 0.6 mm^3/year, respectively, for acetabular liners and femoral heads, after a minimum of six months duration in situ[57].

As in simulator studies, less wear has been observed using CoC bearings. Moreover, aseptic loosening in THAs can be reduced by applying CoC and featuring debris that appears more bioinert than the polyethylene variant [5].

Although previous studies have not yet demonstrated this outcome, it can only become evident after an extended follow-up period. The current investigation, as well as previously discussed research featuring short-term to medium-term follow-ups, showed the tendency for revisions resulting from aseptic loosening to undoubtedly be connected to component fixations when compared to the phenomenon of wear [58–60].

Even though they demonstrate more intraoperative implant fractures and squeaking, the meta-analysis data observed from the randomized controlled trial studies by Hu *et al.* showed support for the application of CoC bearing surfaces, with lower revision rate and reduced propensity for radiolucent line, osteolysis, dislocation, and aseptic loosening to occur, when compared to MoP [61].

Furthermore, a study based on the midterm follow-up by Bouras *et al.* demonstrated a good survival rate and a lower revision rate in terms of aseptic loosening following the use of Zweymuller-Plus THAs characterized by the CoC bearing [62].

Ceramic fracture

A commonly discussed concern regarding CoC bearing surfaces is the possibility of ceramic fractures, as noted in reference [38]. Studies have reported that the incidence of fractures associated with ceramic components ranges from 0.01% to 3.5% of all cases [21,36,63].

In recent years, modern ceramic materials used in joint arthroplasty differ significantly from their counterparts in the 1970s, which were notorious for their high fracture rates [64,65].

Contemporary ceramics in the field demonstrate improved mechanical attributes, primarily attributed to heightened density and decreased grain size achieved through sophisticated manufacturing methods such as hot isostatic pressing and enhanced material compositions. Ceramic fractures typically stem from the progression of cracks induced by inherent material flaws or specific events, which extend, induce fatigue, and ultimately culminate in fractures. Consequently, meticulous attention to precise component assembly prior to implantation is of paramount importance [66]. Improper engagement between titanium shell tapers and ceramic liners can potentially trigger ceramic liner fractures or chipping during insertion.

A study conducted by Koo *et al.* involving 24 patients who received BIOLOX forte CoC bearings after ceramic head fractures revealed that five patients required a second revision, with two patients undergoing three revisions. The reported incidence of fractures associated with ceramic components varies between 0.01% and 3.5% in the literature [63]. Notably, the cup angle of CoC bearings may influence the wear patterns and fracture risk, as suggested by Leslie IJ *et al.* [67].

Another study by Ha *et al.* observed 144 hips in 122 patients over a minimum 36-month follow-up period, revealing that acetabular cups with fractures had a higher anteversion incidence than those without fractures. Fractures tended to occur during squatting, hyperflexion, and broad hip abduction, highlighting the role of impingement, particularly in patients from cultures where squatting is habitual [68,69].

Traina *et al.* found that five out of six patients requiring revision surgery due to ceramic fractures had BIOLOX forte-on-BIOLOX forte bearings [21], while smaller series reported fracture rates ranging from 0% to 2% in BIOLOX forte components [70,71].

The introduction of zirconia platelet-based BIOLOX delta, toughened with alumina, has reduced fracture risk compared to the alumina-based BIOLOX forte. Ex vivo studies support the improved resistance to fractures following this enhancement [21].

Hoskins *et al.* analyzed data from the Australian Joint Replacement Registry, revealing higher breakage rates in alumina-based bearings compared to mixed ceramics, especially for heads with diameters measuring 36-38mm [72]. Smaller femoral heads (28mm) also exhibited a higher propensity to break [36,73].

Traina *et al.* also found that 28mm heads with short neck tapers were more prone to fractures than longer tapers, although complete neck length data in device histories is lacking. Besides material factors, ceramic fractures can result from trauma, debris interference, surgical handling, dislocations, and design mismatches between ceramic heads and metal tapers[73].

Lee *et al.* proposed preventive measures, including the use of a metal shell with an 18° taper angle, a 32/36-mm Delta ceramic bearing, and a stem with a reduced neck outline to mitigate ceramic fractures [74].

Hernigou *et al.* suggest that in cases of head fracture, the intact ceramic liner should be retained, but a new head on a new taper should be inserted to prevent crack propagation. Similarly, in cases of ceramic liner fracture, replacing it with a new ceramic liner necessitates the removal of the shell to obtain a new Morse taper [39].

In contrast, Hannouche *et al.*, in a retrospective study, reported no fractures of ceramic heads implanted on a previous titanium trunion. However, they recommend inspecting the Morse taper for imperfections or small cracks when preserving it [75].

Considering personal clinical experience, the author proposes an alternative approach involving the use of commercially available head-neck metal adapters, such as the MereteTM, BioBallTM system (Merete Medical, Berlin, Germany), often considered in off-label usage [76].

Squeaking

The term squeak is a sound that others can potentially hear, which develops from THAs while in motion. This sound may be described as clicking, squeaking, or grating [77].

Squeaking is not limited solely to Ceramic-on-Ceramic (CoC) bearing surfaces. Historical records indicate that the occurrence of squeaking can be traced back to the introduction of Judet's acrylic hemiarthroplasty in 1946. Furthermore, various bearing surfaces, including specific Metal-on-Metal (MoM) configurations, have also been associated with noise generation [78].

The generation of squeaking noises remains a common complication documented after THA using ceramic-on-ceramic CoC. This may be anything from 0.3 to 20.9% of the total [77,79,80].

Eiden *et al.* examined the synovia-like interface membrane (SLIM) in ceramic squeaking hip endoprostheses. Their subsequent studies found that squeaking revisions accounted for 0.40% of the 1733 total hip joint prosthesis pathology cases. They proposed a pathogenetic relationship between SLIM types I/IV and squeaking. These SLIM variations displayed partly independent, mainly mild inflammation, and partly relied on faint ceramic microscopic particles. Oil-Red positive macrophages and hemosiderin suggested Synovial tissue damage. These macrophages also implicated biomechanical impingement (misload) and associated dysfunction as contributors to the squeaking phenomenon [81].

Ki *et al.* observed a link between higher BMI and increased squeaking occurrence [82]. Scott *et al.*'s extensive meta-analysis similarly highlighted BMI as a significant patient-related risk factor, but no significant correlations were found with other patient demographics, including gender, age, sex, weight, height, or surgical side.

Moreover, no significant correlation was identified between squeaking and the presence of raised metallic rims on acetabular components or the orientation of the acetabular cup [78].

Chevillotte *et al.* examined nine ceramic implants that underwent revisions for various reasons. Two of these revisions were prompted by squeaking, four due to recurrent dislocations, one linked to aseptic loosening, and two related to instability. Their hypothesis focused on cup design and orientation issues leading to impingement, potentially causing lubrication-related problems. This can result in metal transfer and stripe wear, commonly observed in squeaking ceramic-on-ceramic bearings [83].

According to Swanson's classification of hip squeak frequency, Grade I indicated that it happened less frequently than once per week, Grade II indicated that it happened between once and four times per week, Grade III indicated that it happened more frequently than four times per week but not on a daily basis, and Grade IV indicated that it happened every day [84].

Notwithstanding the manifold benefits associated with the utilization of ceramic-on-ceramic bearings, particularly regarding wear reduction, which holds significant appeal for the younger, more physically active patient demographic, it is imperative to engage in informed patient counseling when contemplating the implementation of ceramic-on-ceramic bearings, primarily with respect to the potential occurrence of audible squeaking phenomena [85].

Squeaking phenomena, as observed in ceramic-on-ceramic THAs, are typically unrelated to adverse events such as fractures, aseptic loosening, osteolysis, subsidence, heterotopic ossification, dislocation, or instability [86–90]. Nevertheless, Walter *et al.* have postulated that ceramic-on-ceramic THAs exhibiting squeaking tendencies may exhibit elevated wear rates when compared to their non-squeaking counterparts [91].

CONCLUSION

In spite of their substantial promise, Ceramic-on-Ceramic bearings remain relatively infrequently employed as a bearing surface in primary total hip arthroplasty. This relative scarcity in usage may be attributed to considerations of cost-effectiveness and the requisite scrupulous surgical technique, aimed at averting recurrent complications. The intermediate-term outcomes associated with CoC bearings are poised to bolster their adoption, particularly among the youthful and highly active patient demographic.

Technological advancements in the production and fabrication of ceramic implants have notably curtailed the incidence of long-standing concerns, notably implant fractures. Notably, the generation of audible noise is generally unlinked with an increased incidence of complications. However, it is imperative to underscore that while occurrences of implant fractures and noise generation have become increasingly rare, their potential occurrence should be diligently communicated to patients as an integral component of the preoperative informed consent process.

CONFLICTS OF INTEREST

The author declares no potential conflicts of interest for this article.

ETHICAL CLEARANCE

Not applicable.

AUTHORS' CONTRIBUTION

Data gathering, idea owner of this study, study design, writing, editing, approval of final draft and submitting manuscript: Khalid M. Alhomayani

REFERENCES

1. Varacallo M, Chakravarty R, Denehy K, Star A. Joint perception and patient perceived satisfaction after total hip and knee arthroplasty in the American population. *J Orthop*. 2018;15(2):495-499. doi:10.1016/j.jor.2018.03.018
2. Singh JA, Chen J, Inacio MCS, Namba RS, Paxton EW. An underlying diagnosis of osteonecrosis of bone is associated with worse outcomes than osteoarthritis after total hip arthroplasty. *BMC Musculoskeletal Disorders*. 2017;18(1):8. doi:10.1186/s12891-016-1385-0
3. Bozic KJ, Kurtz S, Lau E, *et al.* The epidemiology of bearing surface usage in total hip arthroplasty in the United States. *J Bone Joint Surg Am*. 2009;91(7):1614-1620. doi:10.2106/JBJS.H.01220
4. Bos I, Willmann G. Morphologic characteristics of periprosthetic tissues from hip prostheses with ceramic-ceramic couples: A comparative histologic investigation of 18 revision and 30 autopsy cases. *Acta orthopaedica Scandinavica*. 2001;72:335-342.

doi:10.1080/000164701753541970

5. Christel PS. Biocompatibility of surgical-grade dense polycrystalline alumina. *Clin Orthop Relat Res*. 1992;(282):10-18.
6. García-Rey E, García-Cimbrelo E. Polyethylene in total hip arthroplasty: half a century in the limelight. *J Orthopaed Traumatol*. 2010;11(2):67-72. doi:10.1007/s10195-010-0091-1
7. Gudena R, Kuna S, Pradhan N. Aseptic loosening of total hip replacement presenting as an anterior thigh mass. *Musculoskelet Surg*. 2013;97(3):247-249. doi:10.1007/s12306-011-0167-y
8. Spinarelli A, Patella V, Petrera M, Abate A, Pesce V, Patella S. Heterotopic ossification after total hip arthroplasty: our experience. *Musculoskelet Surg*. 2011;95(1):1-5. doi:10.1007/s12306-010-0091-6
9. Clark CR. A potential concern in total joint arthroplasty: systemic dissemination of wear debris. *J Bone Joint Surg Am*. 2000;82(4):455-456. doi:10.2106/00004623-200004000-00001
10. Al-Saffar N. Early clinical failure of total joint replacement in association with follicular proliferation of B-lymphocytes: a report of two cases. *J Bone Joint Surg Am*. 2002;84(12):2270-2273. doi:10.2106/00004623-200212000-00022
11. Dunstan E, Ladon D, Whittingham-Jones P, Carrington R, Briggs TWR. Chromosomal aberrations in the peripheral blood of patients with metal-on-metal hip bearings. *J Bone Joint Surg Am*. 2008;90(3):517-522. doi:10.2106/JBJS.F.01435
12. Jacobs JJ, Urban RM, Hallab NJ, Skipor AK, Fischer A, Wimmer MA. Metal-on-metal bearing surfaces. *J Am Acad Orthop Surg*. 2009;17(2):69-76. doi:10.5435/00124635-200902000-00003
13. Visuri T, Pukkala E, Paavolainen P, Pulkkinen P, Riska EB. Cancer risk after metal on metal and polyethylene on metal total hip arthroplasty. *Clin Orthop Relat Res*. 1996;(329 Suppl):S280-289. doi:10.1097/00003086-199608001-00025
14. Thyssen JP, Jakobsen SS, Engkilde K, Johansen JD, Søballe K, Menné T. The association between metal allergy, total hip arthroplasty, and revision. *Acta Orthop*. 2009;80(6):646-652. doi:10.3109/17453670903487008
15. Cooper HJ. The local effects of metal corrosion in total hip arthroplasty. *Orthop Clin North Am*. 2014;45(1):9-18. doi:10.1016/j.ocl.2013.08.003
16. Cooper HJ, Della Valle CJ, Berger RA, *et al.* Corrosion at the head-neck taper as a cause for adverse local tissue reactions after total hip arthroplasty. *J Bone Joint Surg Am*. 2012;94(18):1655-1661. doi:10.2106/jbjs.k.01352
17. Meyer H, Mueller T, Goldau G, Chamaon K, Ruetschi M, Lohmann CH. Corrosion at the cone/taper interface leads to failure of large-diameter metal-on-metal total hip arthroplasties. *Clin Orthop Relat Res*. 2012;470(11):3101-3108. doi:10.1007/s11999-012-2502-5
18. Chana R, Esposito C, Campbell PA, Walter WK, Walter WL. Mixing and matching causing taper wear: corrosion associated with pseudotumour formation. *J Bone Joint Surg Br*. 2012;94(2):281-286. doi:10.1302/0301-620X.94B2.27247
19. Gill IPS, Webb J, Sloan K, Beaver RJ. Corrosion at the neck-stem junction as a cause of metal ion release and pseudotumour formation. *J Bone Joint Surg Br*. 2012;94(7):895-900. doi:10.1302/0301-620X.94B7.29122
20. Shariff MSM, Ngadiron H, Azizan N, Hayati F, Ariffin AC. Total Hip Replacement in a Systemic Lupus Erythematosus Patient. *Bangladesh Journal of Medical Science*. 2020;19(2):322-325. doi:10.3329/bjms.v19i2.45016
21. Traina F, De Fine M, Di Martino A, Faldini C. Fracture of ceramic bearing surfaces following total hip replacement: a systematic review. *Biomed Res Int*. 2013;2013:157247. doi:10.1155/2013/157247
22. Finkbone PR, Severson EP, Cabanela ME, Trousdale RT. Ceramic-on-ceramic total hip arthroplasty in patients younger than 20 years. *J Arthroplasty*. 2012;27(2):213-219. doi:10.1016/j.arth.2011.05.022
23. Kamath AF, Sheth NP, Hosalkar HH, Babatunde OM, Lee GC, Nelson CL. Modern total hip arthroplasty in patients younger than 21 years. *J Arthroplasty*. 2012;27(3):402-408. doi:10.1016/j.arth.2011.04.042
24. Faldini C, Miscione MT, Chehrassan M, *et al.* Congenital hip dysplasia treated by total hip arthroplasty using cementless tapered stem in patients younger than 50 years old: results after 12-years follow-up. *J Orthop Traumatol*. 2011;12(4):213-218. doi:10.1007/s10195-011-0170-y
25. Boutin P. [Total arthroplasty of the hip by fritted aluminum prosthesis. Experimental study and 1st clinical applications]. *Rev Chir Orthop Reparatrice Appar Mot*. 1972;58(3):229-246.
26. Hannouche D, Hamadouche M, Nizard R, Bizot P, Meunier A, Sedel L. Ceramics in total hip replacement. *Clin Orthop Relat Res*. 2005;(430):62-71. doi:10.1097/01.blo.0000149996.91974.83
27. Khalifa AA, Bakr HM. Updates in biomaterials of bearing surfaces in total hip arthroplasty. *Arthroplasty*. 2021;3(1):32. doi:10.1186/s42836-021-00092-6
28. Affatato S, Modena E, Toni A, Taddei P. Retrieval analysis of three generations of Biolox® femoral heads: spectroscopic and SEM characterisation. *J Mech Behav Biomed Mater*. 2012;13:118-128. doi:10.1016/j.jmbbm.2012.04.003
29. Affatato S, Jaber SA, Taddei P. Ceramics for Hip Joint Replacement. In: Zivic F, Affatato S, Trajanovic M, Schnabelrauch M, Grujovic N, Choy KL, eds. *Biomaterials in Clinical Practice*. Springer International Publishing; 2018:167-181. doi:10.1007/978-3-319-68025-5_7
30. McEntire B, Bal B, Rahaman M, *et al.* Ceramics and Ceramic Coatings in Orthopaedics. *Journal of the European Ceramic Society*. 2015;35(16):4327-4369. doi:10.1016/j.jeurceramsoc.2015.07.034
31. Porat M, Parvizi J, Sharkey PF, Berend KR, Lombardi AV, Barrack RL. Causes of Failure of Ceramic-on-Ceramic and Metal-on-Metal Hip Arthroplasties. *Clin Orthop Relat Res*. 2012;470(2):382-387. doi:10.1007/s11999-011-2161-y
32. Willert HG, Buchhorn GH, Fayyazi A, *et al.* Metal-on-metal bearings and hypersensitivity in patients with artificial hip joints. A clinical and histomorphological study. *J Bone Joint Surg Am*. 2005;87(1):28-36. doi:10.2106/JBJS.A.02039pp
33. Fisher J, Jin Z, Tipper J, Stone M, Ingham E. Tribology of alternative bearings. *Clin Orthop Relat Res*. 2006;453:25-34. doi:10.1097/01.blo.0000238871.07604.49
34. Kurtz SM, Gawel HA, Patel JD. History and systematic review of wear and osteolysis outcomes for first-generation highly crosslinked polyethylene. *Clin Orthop Relat Res*. 2011;469(8):2262-2277. doi:10.1007/s11999-011-1872-4
35. Korim M, Scholes S, Unsworth A, Power R. Retrieval analysis of alumina ceramic-on-ceramic bearing couples. *Acta Orthop*. 2014;85(2):133-140. doi:10.3109/17453674.2014.894390

36. D'Antonio JA, Sutton K. Ceramic materials as bearing surfaces for total hip arthroplasty. *J Am Acad Orthop Surg*. 2009;17(2):63-68.
37. Kocagoz SB, Underwood RJ, MacDonald DW, Gilbert JL, Kurtz SM. Ceramic Heads Decrease Metal Release Caused by Head-taper Fretting and Corrosion. *Clin Orthop Relat Res*. 2016;474(4):985-994. doi:10.1007/s11999-015-4683-1
38. Sentuerk U, von Roth P, Perka C. Ceramic on ceramic arthroplasty of the hip: new materials confirm appropriate use in young patients. *Bone Joint J*. 2016;98-B(1 Suppl A):14-17. doi:10.1302/0301-620X.98B1.36347
39. Hernigou P, Roubineau F, Bouthors C, Flouzat-Lachaniette CH. What every surgeon should know about Ceramic-on-Ceramic bearings in young patients. *EFORT Open Rev*. 2016;1(4):107-111. doi:10.1302/2058-5241.1.000027
40. 15th Annual Report 2018 National Joint Registry for England, Wales, Northern Ireland and the Isle of Man Surgical data to 31 December 2017. https://www.hqip.org.uk/wp-content/uploads/2018/11/NJR-15th-Annual-Report-2018.pdf
41. Peters RM, Van Steenbergen LN, Stevens M, Rijk PC, Bulstra SK, Zijlstra WP. The effect of bearing type on the outcome of total hip arthroplasty: Analysis of 209,912 primary total hip arthroplasties registered in the Dutch Arthroplasty Register. *Acta Orthopaedica*. 2018;89(2):163-169. doi:10.1080/17453674.2017.1405669
42. REPORT of R.I.P.O. Regional Register of Orthopaedic Prosthetic Implantology. OVERALL DATA HIP, KNEE AND SHOULDER ARTHROPLASTY IN EMILIA-ROMAGNA REGION (ITALY) 2000-2016. Published online April 13, 2016. http://ripo.cineca.it/pdf/report_eng_2016.pdf
43. Australian Orthopaedic Association National Joint Replacement Registry (AOANJRR). Hip, Knee & Shoulder Arthroplasty: 2018 Annual Report. Data period 1 September 1999 – 31 December 2017. Adelaide: AOA, 2018:157. https://aoanjrr.sahmri.com/documents/10180/576950/Hip%2C%20Knee%20%26%20Shoulder%20Arthroplasty
44. Sharplin P, Wyatt MC, Rothwell A, Frampton C, Hooper G. Which is the best bearing surface for primary total hip replacement? A New Zealand Joint Registry study. *HIP International*. 2018;28(4):352-362. doi:10.5301/hipint.5000585
45. Zheng C, Xu J, Wu L, Wu Y, Liu Y, Shen B. Comparisons of Different Bearing Surfaces in Cementless Total Hip Arthroplasty: A Systematic Review and Bayesian Network Analysis. *J Arthroplasty*. 2023;38(3):600-609. doi:10.1016/j.arth.2022.10.016
46. Garellick G, Rogmark C, Rolfson O, Herberts P. Swedish Hip Arthroplasty Register. Annual Report. 2011. https://registercentrum.blob.core.windows.net/shpr/r/Annual-report-2011-BJ0dK8Toe.pdf
47. Dargel J, Oppermann J, Brüggemann GP, Eysel P. Dislocation following total hip replacement. *Dtsch Arztebl Int*. 2014;111(51-52):884-890. doi:10.3238/arztebl.2014.0884
48. Woo RY, Morrey BF. Dislocations after total hip arthroplasty. *J Bone Joint Surg Am*. 1982;64(9):1295-1306.
49. Lachiewicz PF. FEMORAL HEAD SIZE: IS BIGGER ALWAYS BETTER? *Orthopaedic Proceedings*. 2018;100-B(SUPP_10):12-12. doi:10.1302/1358-992X.2018.10.012
50. Al-Hajjar M, Fisher J, Tipper JL, Williams S, Jennings LM. Wear of 36-mm BIOLOX(R) delta ceramic-on-ceramic bearing in total hip replacements under edge loading conditions. *Proc Inst Mech Eng H*. 2013;227(5):535-542. doi:10.1177/0954411912474613
51. Hernigou P, Homma Y, Pidet O, Guissou I, Hernigou J. Ceramic-on-ceramic Bearing Decreases the Cumulative Long-term Risk of Dislocation. *Clin Orthop Relat Res*. 2013;471(12):3875-3882. doi:10.1007/s11999-013-2857-2
52. Lenguerrand E, Whitehouse MR, Beswick AD, *et al.* Risk factors associated with revision for prosthetic joint infection after hip replacement: a prospective observational cohort study. *Lancet Infect Dis*. 2018;18(9):1004-1014. doi:10.1016/S1473-3099(18)30345-1
53. Madanat R, Laaksonen I, Graves SE, Lorimer M, Muratoglu O, Malchau H. Ceramic bearings for total hip arthroplasty are associated with a reduced risk of revision for infection. *Hip Int*. 2018;28(3):222-226. doi:10.1177/1120700018776464
54. Jacobs JJ, Shanbhag A, Glant TT, Black J, Galante JO. Wear Debris in Total Joint Replacements. *J Am Acad Orthop Surg*. 1994;2(4):212-220. doi:10.5435/00124635-199407000-00004
55. Clarke IC, Good V, Williams P, *et al.* Ultra-low wear rates for rigid-on-rigid bearings in total hip replacements. *Proc Inst Mech Eng H*. 2000;214(4):331-347. doi:10.1243/0954411001535381
56. Stewart TD, Tipper JL, Insley G, Streicher RM, Ingham E, Fisher J. Long-term wear of ceramic matrix composite materials for hip prostheses under severe swing phase microseparation. *J Biomed Mater Res B Appl Biomater*. 2003;66(2):567-573. doi:10.1002/jbm.b.10035
57. Lusty PJ, Watson A, Tuke MA, Walter WL, Walter WK, Zicat B. Wear and acetabular component orientation in third generation alumina-on-alumina ceramic bearings: an analysis of 33 retrievals [corrected]. *J Bone Joint Surg Br*. 2007;89(9):1158-1164. doi:10.1302/0301-620X.89B9.19282
58. Garcia-Rey E, Cruz-Pardos A, Garcia-Cimbrelo E. Alumina-on-alumina total hip arthroplasty in young patients: diagnosis is more important than age. *Clin Orthop Relat Res*. 2009;467(9):2281-2289. doi:10.1007/s11999-009-0904-9
59. Johansson HR, Johnson AJ, Zywiel MG, Naughton M, Mont MA, Bonutti PM. Does acetabular inclination angle affect survivorship of alumina-ceramic articulations? *Clin Orthop Relat Res*. 2011;469(6):1560-1566. doi:10.1007/s11999-010-1623-y
60. Khatod M, Cafri G, Namba RS, Inacio MCS, Paxton EW. Risk factors for total hip arthroplasty aseptic revision. *J Arthroplasty*. 2014;29(7):1412-1417. doi:10.1016/j.arth.2014.01.023
61. Hu D, Tie K, Yang X, Tan Y, Alaidaros M, Chen L. Comparison of ceramic-on-ceramic to metal-on-polyethylene bearing surfaces in total hip arthroplasty: a meta-analysis of randomized controlled trials. *J Orthop Surg Res*. 2015;10:22. doi:10.1186/s13018-015-0163-2
62. Bouras T, Repantis T, Fennema P, Korovessis P. Low aseptic loosening and revision rate in Zweymüller-Plus total hip arthroplasty with ceramic-on-ceramic bearings. *Eur J Orthop Surg Traumatol*. 2014;24(8):1439-1445. doi:10.1007/s00590-013-1314-y
63. Koo KH, Ha YC, Jung WH, Kim SR, Yoo JJ, Kim HJ. Isolated fracture of the ceramic head after third-generation alumina-on-alumina total hip arthroplasty. *J Bone Joint Surg Am*. 2008;90(2):329-336. doi:10.2106/JBJS.F.01489
64. Chang JD, Kamdar R, Yoo JH, Hur M, Lee SS. Third-generation

ceramic-on-ceramic bearing surfaces in revision total hip arthroplasty. *J Arthroplasty*. 2009;24(8):1231-1235. doi:10.1016/j.arth.2009.04.016

65. Yoo JJ, Kim YM, Yoon KS, Koo KH, Song WS, Kim HJ. Alumina-on-alumina total hip arthroplasty. A five-year minimum follow-up study. *J Bone Joint Surg Am*. 2005;87(3):530-535. doi:10.2106/JBJS.D.01753
66. PANDORF, T. How important it is to use clean taper fixations. In: ; 2009.
67. Leslie IJ, Williams S, Isaac G, Ingham E, Fisher J. High cup angle and microseparation increase the wear of hip surface replacements. *Clin Orthop Relat Res*. 2009;467(9):2259-2265. doi:10.1007/s11999-009-0830-x
68. Ha YC, Kim SY, Kim HJ, Yoo JJ, Koo KH. Ceramic liner fracture after cementless alumina-on-alumina total hip arthroplasty. *Clin Orthop Relat Res*. 2007;458:106-110. doi:10.1097/BLO.0b013e3180303e87
69. Lopes R, Philippeau JM, Passuti N, Gouin F. High rate of ceramic sandwich liner fracture. *Clin Orthop Relat Res*. 2012;470(6):1705-1710. doi:10.1007/s11999-012-2279-6
70. Yeung E, Bott PT, Chana R, *et al.* Mid-term results of third-generation alumina-on-alumina ceramic bearings in cementless total hip arthroplasty: a ten-year minimum follow-up. *J Bone Joint Surg Am*. 2012;94(2):138-144. doi:10.2106/JBJS.J.00331
71. Epinette JA, Manley MT. No differences found in bearing related hip survivorship at 10-12 years follow-up between patients with ceramic on highly cross-linked polyethylene bearings compared to patients with ceramic on ceramic bearings. *J Arthroplasty*. 2014;29(7):1369-1372. doi:10.1016/j.arth.2014.02.025
72. Hoskins W, Rainbird S, Peng Y, Lorimer M, Graves SE, Bingham R. Incidence, Risk Factors, and Outcome of Ceramic-On-Ceramic Bearing Breakage in Total Hip Arthroplasty. *J Arthroplasty*. 2021;36(8):2992-2997. doi:10.1016/j.arth.2021.03.021
73. Traina F, Tassinari E, De Fine M, Bordini B, Toni A. Revision of ceramic hip replacements for fracture of a ceramic component: AAOS exhibit selection. *J Bone Joint Surg Am*. 2011;93(24):e147. doi:10.2106/JBJS.K.00589
74. Lee YK, Lim JY, Ha YC, Kim TY, Jung WH, Koo KH. Preventing ceramic liner fracture after Delta ceramic-on-ceramic total hip arthroplasty. *Arch Orthop Trauma Surg*. 2021;141(7):1155-1162. doi:10.1007/s00402-020-03515-2
75. Hannouche D, Delambre J, Zadegan F, Sedel L, Nizard R. Is There a Risk in Placing a Ceramic Head on a Previously Implanted Trunion? *Clin Orthop Relat Res*. 2010;468(12):3322-3327. doi:10.1007/s11999-010-1505-3
76. Novoa CD, Citak M, Zahar A, López RE, Gehrke T, Rodrigo JL. The Merete BioBall system in hip revision surgery: A systematic review. *Orthop Traumatol Surg Res*. 2018;104(8):1171-1178. doi:10.1016/j.otsr.2018.06.016
77. Keurentjes JC, Kuipers RM, Wever DJ, Schreurs BW. High incidence of squeaking in THAs with alumina ceramic-on-ceramic bearings. *Clin Orthop Relat Res*. 2008;466(6):1438-1443. doi:10.1007/s11999-008-0177-8
78. Stanat SJC, Capozzi JD. Squeaking in third- and fourth-generation ceramic-on-ceramic total hip arthroplasty: meta-analysis and systematic review. *J Arthroplasty*. 2012;27(3):445-453. doi:10.1016/j.arth.2011.04.031
79. Lusty PJ, Tai CC, Sew-Hoy RP, Walter WL, Walter WK, Zicat BA. Third-generation alumina-on-alumina ceramic bearings in cementless total hip arthroplasty. *J Bone Joint Surg Am*. 2007;89(12):2676-2683. doi:10.2106/JBJS.F.01466
80. Goldhofer MI, Munir S, Levy YD, Walter WK, Zicat B, Walter WL. Increase in Benign Squeaking Rate at Five-Year Follow-Up: Results of a Large Diameter Ceramic-on-Ceramic Bearing in Total Hip Arthroplasty. *J Arthroplasty*. 2018;33(4):1210-1214. doi:10.1016/j.arth.2017.11.044
81. Eiden S, Bormann T, Kretzer JP, Dieckmann R, Krenn V. [Typing and particle analysis of squeaking hip endoprostheses : First histopathological analysis to examine the squeaking pathogenesis of ceramic-on-ceramic bearings]. *Orthopade*. 2021;50(12):1032-1038. doi:10.1007/s00132-021-04133-5
82. Ki SC, Kim BH, Ryu JH, Yoon DH, Chung YY. Squeaking sound in total hip arthroplasty using ceramic-on-ceramic bearing surfaces. *J Orthop Sci*. 2011;16(1):21-25. doi:10.1007/s00776-010-0005-3
83. Chevillotte C, Trousdale RT, An KN, Padgett D, Wright T. Retrieval analysis of squeaking ceramic implants: are there related specific features? *Orthop Traumatol Surg Res*. 2012;98(3):281-287. doi:10.1016/j.otsr.2011.12.003
84. Swanson TV, Peterson DJ, Seethala R, Bliss RL, Spellmon CA. Influence of prosthetic design on squeaking after ceramic-on-ceramic total hip arthroplasty. *J Arthroplasty*. 2010;25(6 Suppl):36-42. doi:10.1016/j.arth.2010.04.032
85. Jarrett CA, Ranawat AS, Bruzzone M, Blum YC, Rodriguez JA, Ranawat CS. The squeaking hip: a phenomenon of ceramic-on-ceramic total hip arthroplasty. *J Bone Joint Surg Am*. 2009;91(6):1344-1349. doi:10.2106/JBJS.F.00970
86. Yang CC, Kim RH, Dennis DA. The squeaking hip: a cause for concern-disagrees. *Orthopedics*. 2007;30(9):739-742. doi:10.3928/01477447-20070901-33
87. Nevelos J, Ingham E, Doyle C, *et al.* Microseparation of the centers of alumina-alumina artificial hip joints during simulator testing produces clinically relevant wear rates and patterns. *J Arthroplasty*. 2000;15(6):793-795. doi:10.1054/arth.2000.8100
88. Gallo J, Goodman SB, Lostak J, Janout M. Advantages and disadvantages of ceramic on ceramic total hip arthroplasty: a review. *Biomed Pap Med Fac Univ Palacky Olomouc Czech Repub*. 2012;156(3):204-212. doi:10.5507/bp.2012.063
89. Tateiwa T, Clarke IC, Williams PA, *et al.* Ceramic total hip arthroplasty in the United States: safety and risk issues revisited. *Am J Orthop (Belle Mead NJ)*. 2008;37(2):E26-31.
90. Ecker TM, Robbins C, van Flandern G, *et al.* Squeaking in total hip replacement: no cause for concern. *Orthopedics*. 2008;31(9):875-876, 884. doi:10.3928/01477447-20080901-11
91. Walter WL, Kurtz SM, Esposito C, *et al.* Retrieval analysis of squeaking alumina ceramic-on-ceramic bearings. *J Bone Joint Surg Br*. 2011;93(12):1597-1601. doi:10.1302/0301-620X.93B12.27529