Articulating components should minimise the generation of wear particles in order to optimize long-term survival of the prosthesis.

A good understanding of tribological properties helps the orthopaedic surgeon to choose the most suitable bearing for each individual patient.

Conventional and highly cross-linked polyethylene articulating either with metal or ceramic, ceramic-on-ceramic and metal-on-metal are the most commonly used bearing combinations.

All combinations of bearing surface have their advantages and disadvantages. An appraisal of the individual patient’s objectives should be part of the assessment of the best bearing surface.

**Keywords:** osteoarthritis; total hip replacement; tribology; wear

Cite this article: Rieker CB. Tribology of total hip arthroplasty prostheses: what an orthopaedic surgeon should know. EFORT Open Rev 2016;1:52-57. DOI: 10.1302/2058-5241.1.000004.

**Introduction**

Although total hip arthroplasty (THA) has provided good results for over forty years, the choice of the optimal bearing surface still remains controversial. Tribology is defined as “the branch of science and technology that deals with the study of friction, wear, and lubrication”. Tribology is fundamental to the function and long-term survival of orthopaedic implants.

With the development of hip implants with metal-on-polyethylene (MoP) bearings in the early 1960s, cases of aseptic loosening of prostheses started to be seen towards the beginning of the 1970s which were not completely explicable at that time. Numerous hypotheses were put forward to try to explain these cases of aseptic loosening, especially one named ‘cement disease’, which subsequently led to the development of uncemented implants.

Following several years of investigation, Willert et al were able to demonstrate that the observed cases of aseptic loosening could be explained by a concept they described as ‘particle disease’. According to these researchers, polyethylene (PE) debris particles are generated in the absence of fluid film lubrication between the femoral head and the acetabular cup, due to abrasive and adhesive wear caused by the relative movements between the two surfaces. Wear particles trigger a series of biochemical reactions, which change the dynamic balance between osteoblasts and osteoclasts. The enhanced osteoclast activity results in osteolysis in the areas affected by a high number of wear particles. This resorption of bone eventually leads to aseptic loosening of implants in the long-term. Osteolysis is directly correlated with the amount of debris particles. In order to maximize implant survival, articulating components should therefore minimize the generation of wear particles of a biologically-critical size, which is, according to Green et al, between 0.3 and 10 µm.

The objective of this overview is to succinctly present the important elements to understand in the tribology of THA. A good understanding of tribological properties helps the orthopaedic surgeon to choose the most suitable bearing solution for each individual patient.

**Conventional polyethylenes**

The MoP first used for total hip prostheses was introduced in 1962 by the British surgeon John Charnley (Fig. 1). This polymer is a high molecular-weight PE with extremely long chains (between 2 and 6 million atomic mass units). For four decades up until the mid-2000s, MoP bearings with head diameters ranging between 22 mm and 32 mm represented the ‘standard’ and they are still commonly used today. Linear wear of MoP bearings is typically within the range of 100 to 300 µm/year. This corresponds to a volumetric wear of around 20 - 150 mm³/year for 28 mm heads. Previous research has suggested that linear wear rates for 22 mm, 28 mm and 32 mm do not vary significantly.

The introduction of ceramic (alumina - aluminium oxide [Al₂O₃]) heads reduced the PE wear by approximately 50%. For 28 mm diameter heads this resulted in a reduction of volumetric wear by approximately 75%, with values between 5 mm and 50 mm³/year. A study by Orishimo has shown a high correlation between volumetric wear and the risk of osteolysis for articulations using conventional PE. It was reported that...
every increase in the amount of volumetric wear of 40 mm$^3$/year triples the long-term risk of osteolysis.

**Highly cross-linked polyethylenes**

Highly cross-linked polyethylenes (HXLPEs) were developed in the 1990s. The cross-linking of polymer chains by forming bonds between them allows the modification of the molecular structure of the PE. This new structure leads to a significantly higher resistance against abrasive and adhesive wear. Cross-linking is achieved by irradiation using either electron beams or gamma rays. For both methods, the cross-links are formed by the reaction of the free radicals that are generated by the irradiation. However, once the cross-linking is achieved, it is of particular importance to eliminate, as far as possible, residual free radicals left over from the process in order to minimise the risk of long-term oxidation. Several approaches are used to remove the free radicals. These include re-melting or thermal annealing treatments in the case of the first generation of cross-linked PEs.

The first generation of HXLPE became clinically available at the end of the 1990s. Initial clinical studies have shown a significant decrease of wear, with reported linear wear rates ranging from between 2 and 20 µm/year, and volumetric wear rates substantially lower than 1 mm$^3$/year for 28 mm prosthetic femoral heads. Since aseptic loosening after THA is rare, survival advantages of HXLPE will inevitably need to be determined in large cohorts, and long observation periods will be required. Recently, the Australian National Joint Replacement Registry reported a significantly lower revision rate for HXLPE compared with standard PE for metal-on-HXLPE, and the 14-year cumulative revision rate decreased from 9.9% to 5.4%. For ceramic-on-HXLPE the ten-year cumulative revision rate decreased from 7.0% to 4.6%. The considerably reduced wear has also allowed an increase of the articulation diameter of the metal prosthetic heads up to 40 mm. In vivo studies have shown that linear wear is virtually independent of the articulation diameter. However, volumetric wear increases with head size. Table 1 demonstrates that volumetric wear increases as a function of the articulation diameter, and that the Metal-on-HXLPE articulation with larger diameters (40 mm and larger) should only be considered for patients where the benefits of a larger diameter head (e.g. reduced risk of head dislocation) outweigh the potential risks associated with an increased volumetric wear rate.

Following reports in several publications that HXLPEs of the first generation (especially those having undergone thermal treatment) can exhibit signs of oxidation, HXLPEs treated with vitamin E were recently introduced (Fig. 2).

Due to its being a highly effective free radical scavenger, Vitamin E helps to neutralise the formation of free radicals responsible for oxidation. Vitamin E can be incorporated either by diffusion, or by blending it into PE before the moulding process.

**Metal-on-metal bearings**

With a first implantation in 1938 by Wiles, the MoM articulation was the first bearing used for THA. Between the 1950s and 1970s, a cast CoCrMo alloy was used widely for these bearings. Primarily due to poor manufacturing tolerances, this historical bearing yielded largely unsatisfactory results.
metric wear. This increase in debris can provoke conditions and independent of cup abduction angle.36 As a result, National Joint Registry data have shown that large diameter MoM hip arthroplasties and resurfacings with MoM bearing surfaces have significantly higher revision rates compared with those with conventional bearings.37 The use of these articulations has been associated with wear-related adverse events, such as soft tissue inflammatory reactions to metal debris, which are summarized under the name ‘adverse reactions to metal debris (ARMD).’ Inflammatory pseudotumours, aseptic lymphocytic vasculitis associated lesions (ALVALs) and metallosis are all examples of ARMDs. The spectrum of ARMD is wide and ranges from small asymptomatic cysts to large soft tissue masses (pseudotumours).37

Ceramic-on-ceramic articulations

After MoM, ceramic-on-ceramic (CoC) articulation, developed in France by Boutin in 1970,38 was the second ‘alternative’ bearing (Fig. 4) to the MoP bearing. Alumina and zirconia (zirconium oxide [ZrO2]) ceramic have historically been used in THA, with alumina being the most frequently used of the two. Alumina has a very low friction coefficient, making it an appropriate choice for an orthopaedic bearing surface. In addition, alumina is bio-compatible, and in vivo its material properties are not affected by ageing. In vitro studies have shown that this articulation also offers the benefit of significantly reducing volumetric wear (within the range of 0.1 mm to 1 mm³/year).39-41 However, under microseparation conditions one study showed that the wear rate increased to almost 2 mm³/million cycles.36

Due to the brittle nature of the alumina components and the catastrophic consequences of a possible fracture with the generation of a large number of small alumina fragments, the use of alumina-on-alumina bearings was not widespread until the early 2000s when the new composite ceramic Biolox Delta (CeramTec; Plochingen, Germany) was introduced. This ceramic is composed of 82% alumina and 17% zirconia (volumetric composition) and has twice the tenacity (resistance to crack propagation) of pure alumina.42 This higher tenacity greatly reduces the risk of fracture. Fracture rates of the femoral head have reduced from 0.021% for alumina-on-alumina (Biolox Forte, Ceramtec; Plochingen, Germany) to 0.003% for Biolox Delta.43 The fracture rate of cup inserts has remained virtually unchanged, however, at a rate of 0.03%. An in vitro study has shown that Biolox Delta has a wear rate < 0.25 mm²/million cycles, even under microseparation conditions and independent of cup abduction angle.36
In spite of its higher fracture-resistance, the use of zirconia as bearing material is less widespread, since alumina is chemically more stable in vivo.

Excellent long-term clinical results have been reported for alumina CoC, with a cumulative survival rate of 99% at ten-year follow-up, and with 84.4% survival after 21 years. Good results have also been reported in young patients (<30 years) without osteolysis, loosening, fractures, or squeaking at a minimum follow-up of 4.5 years. Moreover, an in vitro study found that large diameter CoC articulation (up to 48 mm) does not result in higher wear rates compared to small bearings (up to 32 mm), and wear rates remained low even under edge-loading conditions. Therefore, latest-generation CoC bearings allow a decrease in the thickness of acetabular components. Because of these advantages, their use has been supported in a patient population requiring large-diameter femoral heads, although it still remains essential that malpositioning is avoided.

First results from the Australian National Joint Replacement Registry confirm that at five years’ follow-up, the revision rate of large-diameter CoC articulations is not inferior to the revision rate of the 32 mm heads.

Noises such as clicking, grinding, clunking, scraping, and squeaking have been reported in the literature as adverse events after CoC implantation, with squeaking being the most common. The reported incidence of squeaking varies between 0.7 – 20.9% of patients, with a meta-analysis revealing 2.4% as pooled incidence. Although the underlying pathomechanics are not completely understood, causative factors mentioned in the literature are sub-optimal component design, insufficient lubrication, edge-loading wear or micro-separation and inadequate component alignment. Squeaking noises may lead to decreased patient satisfaction, and even to revision. Owen et al reported a revision rate for squeaking of 0.2%.

Ceramic-on-metal articulations

The use of a low-wearing ceramic-on-metal (CoM) articulation within THA was first reported by Firkins et al in 2001. The differential hardness of the bearing partners was thought to reduce the squeaking issues found with CoC bearings, as well as the wear-related adverse events found with MoM articulations. CoM bearings have low in vitro wear, but in vivo studies seem to indicate that the post-operative serum ion levels of this bearing type are still significantly elevated, and it remains to be seen whether this bearing type therefore, in the light of the remaining fracture risk for the ceramic femoral head component, yields any advantages over MoM bearings.

Conclusions

All combinations of bearing surface have advantages and disadvantages. An appraisal of the individual patient’s objectives should be part of the assessment of the best bearing surface.

At present, it is possible to make the following general recommendations for bearing surfaces. Bearing surfaces with standard PE are still considered good options that perform very well in elderly, low-demand patients who have a life expectancy of < 15 years, while alternatives have emerged for younger, higher-demand patients.

While MoM articulations with small head diameters (28 and 32 mm) presented good long-term clinical results, clinical issues with larger diameter heads shed bad light on the whole technology such that MoM articulations are not expected to be used on a large scale in the future. According to Migaud et al, the only exception for active patients might be resurfacing arthroplasty, for which there are currently no credible alternatives to MoM bearings.

CoC bearing combinations yield good clinical results and therefore remain a viable option in the younger and more active patient population. Due to its wear characteristics, CoC is particularly suitable for patients requiring large femoral head diameters (40 mm, 44 mm and 48 mm). The consequences of CoM bearings are unclear, as it remains to be seen whether this bearing type, in the light of the remaining fracture risk for the ceramic femoral head component and elevated wear as seen in in vivo studies, yields any clinical advantages over MoM bearings.

A bearing combination comprising HXLPE with either a metal or a ceramic head offers a highly promising bearing solution that displays low wear, while being more forgiving (for the cup positioning) than alternative bearings. This technology makes it possible to minimize the risk of revision after ten years or more, and allows the use of prosthetic femoral heads with diameters that have a low dislocation rate (32 mm or 36 mm). However, HXLPEs with already-published risks of oxidation (especially those
having undergone a thermal treatment) should be used with caution in order to avoid possible long-term failure. The choice of whether to use HXLP in combination with a metal or a ceramic head is secondary, as similarly low revision rates have been obtained with both bearing materials. More recently, the enhancement of HXLP with vitamin E shows high fatigue strength, which may potentially lead to a further decrease in PE wear. Although early results are promising, longer follow-up and large study cohorts will be required to determine if these will translate into improved clinical performance and durability of these implants.

**AUTHOR INFORMATION**

Zimmer Biomet, Switzerland.

Correspondence should be sent to Claude B. Rieker, Zimmer Biomet EMEA GmbH, Sulzerallee 8, CH 8404 Winterthur, Switzerland.

Email: claude.rieker@zimmerbiomet.com

**CONFLICT OF INTEREST**

The author is an employee of Zimmer Biomet GmbH, Winterthur, Switzerland.

**FUNDING**

The author or one or more of the authors have received or will receive benefits for personal or professional use from a commercial party related directly or indirectly to the subject of this article.

**LICENCE**

© 2016 The author(s)

This article is distributed under the terms of the Creative Commons Attribution-NonCommercial 4.0 License (http://creativecommons.org/licenses/by-nc/4.0/) which permits non-commercial use, reproduction and distribution of the work without further permission provided the original work is attributed.

**REFERENCES**

1. No authors listed. Chambers 21st Century Dictionary. http://www.chambers.co.uk/dictionaries/the-chambers-dictionary.php (date last accessed: 22 January 2016).

2. Willert HG, Semlitsch M. Reactions of the articular capsule to wear products of artificial joint prostheses. *J Biomed Mater Res* 1977;11:157–164.

3. Sochart DH. Relationship of acetabular wear to osteolysis and loosening in total hip arthroplasty. *Clin Orthop Relat Res* 1999;363:153–159.

4. Dumbleton JH, Manley MT, Edidin AA. A literature review of the association between wear rate and osteolysis in total hip arthroplasty. *J Arthroplasty* 2002;17:649–661.

5. Wan Z, Dorr LD. Natural history of femoral focal osteolysis with proximal ingrowth smooth stem implant. *J Arthroplasty* 1996;11:718–725.

6. Orishimo KF, Claus AM, Sychterz CJ, Engh CA. Relationship between polyethylene wear and osteolysis in hips with a second-generation porous-coated cementless cup after seven years of follow-up. *J Bone Joint Surg [Am]* 2003;85-A:1095–1099.

7. Green TR, Fisher J, Matthews JB, Stone MH, Ingham E. Effect of size and dose on bone resorption activity of macrophages by in vitro clinically relevant ultra high molecular weight polyethylene particles. *J Biomed Mater Res* 2000;53:490–497.

8. Charnley J, Halley DK. Rate of wear in total hip replacement. *Clin Orthop Relat Res* 1975;112:110–119.

9. No authors listed. National Joint Replacement Registry annual report 2015. Adelaide, Australia: University of Adelaide, 2015. https://www.njrr.org.au/docs/default-source/annual-reports/annual-report-2014-2015_final_webpdf/pdfvnr=4 (date last accessed 10 February 2016).

10. Semlitsch M, Willert HG. Clinical wear behaviour of ultra-high molecular polyethylene cups paired with metal and ceramic ball heads in comparison to metal-on-metal pairings of hip joint replacements. *Proc Inst Mech Eng H* 1997;211:73–88.

11. Bigsby RJ, Auger DD, Jin ZM, et al. A comparative tribological study of the wear of composite cushion cups in a physiological hip joint simulator. *J Biomech* 1998;31:363–369.

12. Livermore J, Istrup D, Morrey B. Effect of femoral head size on wear of the polyethylene acetabular component. *J Bone Joint Surg [Am]* 1994;76-A:518–528.

13. Meftah M, Klingenstein GG, Yun R, Ranawat AS, Ranawat CS. Long-term performance of ceramic and metal femoral heads on conventional polyethylene in young and active patients: a matched-pair analysis. *J Bone Joint Surg [Am]* 2013;95-A:1193–1197.

14. Muratoglu OK, Bradson CR, O’Connor DO, Jasty M, Harris WH. A novel method of cross-linking ultra-high-molecular-weight polyethylene to improve wear, reduce oxidation, and retain mechanical properties. Recipient of the 1999 HAP Paul Award. *J Arthroplasty* 2001;16:149–160.

15. Dion NT, Bradson C, Muratoglu O, Freiberg AA. Durability of highly cross-linked polyethylene in total hip and total knee arthroplasty. *Orthop Clin North Am* 2015;46:321–327.

16. Kurz SM, Gawel HA, Patel JD. History and systematic review of wear and osteolysis outcomes for first-generation highly crosslinked polyethylene. *Clin Orthop Relat Res* 2011:64;2262–2277.

17. Digas G, Kährholm J, Thanner J, Herbergs P. 5-year experience of highly cross-linked polyethylene in cemented and uncemented sockets: two randomized studies using radiostereometric analysis. *Acta Orthop* 2007;78:746–754.

18. Thomas GE, Simpson DJ, Mehmood S, et al. The seven-year wear of highly cross-linked polyethylene in total hip arthroplasty: a double-blind, randomized controlled trial using radiostereometric analysis. *J Bone Joint Surg [Am]* 2013;95-A:716–722.

19. Stambough JB, Pashos G, Bohnenkamp FC, et al. Long-term results of total hip arthroplasty with 28-millimeter cobalt-chromium femoral heads on highly cross-linked polyethylene in patients 50 years and less. *J Arthroplasty* 2016;31:162–167.

20. Keeney JA, Martell JM, Pashos G, et al. Highly cross-linked polyethylene improves wear and mid-term failure rates for young total hip arthroplasty patients. *Hip Int* 2015;25:435–441.

21. Reinitz SD, Currier BH, Van Citters DW, Levine RA, Collier JP. Oxidation and other property changes of retrieved sequentially annealed UHMWPE acetabular and tibial bearings. *J Biomed Mater Res B Appl Biomater* 2015;103:578–586.

22. Oral E, Muratoglu OK. Vitamin E diffused, highly crosslinked UHMWPE: a review. *Int Orthop* 2011;35:215–223.

23. Amstutz HC, Grigoris P. Metal-on-metal articulation for artificial hip joints: laboratory study and clinical results. *Proc Inst Mech Eng H* 1996;210:223–232.
26. Rieker CB, Schön R, Konrad R, et al. Influence of the clearance on in-vitro tribology of large diameter metal-on-metal articulations pertaining to resurfacing hip implants. Orthop Clin North Am 2005;36:135-142.

27. Farrar R, Schmidt MB. The effect of diametral clearance on wear between head and cup for metal on metal articulations. 43rd Annual Meeting Orthopedic Research Society. Trans 43rd ORS, February 1997:71.

28. Shen MC, Rieker CB, Gneep P, Liebentritt G, Schoen R. Effect of clearance on frictional torque characteristics of metal-on-metal THA. 51st Annual Meeting of the Orthopaedic Research Society, Washington, DC, 19-21 February 2005; http://www.aor.org/Transactions/v51/1995.pdf (date last accessed 28 January 2016).

29. Tuke MA, Scott G, Roques A, Hu QX, Taylor A. Design considerations and life prediction of metal-on-metal bearings: the effect of clearance. J Bone Joint Surg [Am] 2008;90-A:134-141.

30. Wagner M, Wagner H. Medium-term results of a modern metal-on-metal system in total hip replacement. Clin Orthop Relat Res 2003;397:123-123.

31. Chan FW, Bobyn JD, Medley JB, Krygier JJ, Tanzer M. The Otto Aufranc Award. Wear and lubrication of metal-on-metal hip implants. Clin Orthop Relat Res 1999;369:12-24.

32. Weber BG, Fiechter T. Polyethylene wear and late loosening of a total prosthesis of the hip joint. New perspectives for metal/metal pairing of the capsule and head. Orthopade 1989;18:370-376 [In German].

33. Inmann MM, Gotterbarm T, Kretzer JP, et al. Minimum ten-year results of a 28-mm metal-on-metal bearing in cementless total hip arthroplasty in patients fifty years of age and younger. Int Orthop 2014;38:929-934.

34. Randelli F, Bacci L, D’Anna A, Visentin O, Randelli G. Cementless Metal-Metal on-Metal total hip arthroplasty at 15 years. J Arthroplasty 2012;27:186-192.

35. Lass R, Grübl A, Kolb A, et al. Primary cementless total hip arthroplasty with second-generation metal-on-metal bearings: a concise follow-up, at a minimum of seventeen years, of a previous report. J Bone Joint Surg [Am] 2014;96-A:637.

36. Al-Hajjar M, Fisher J, Williams S, Tipper JL, Jennings LM. Effect of femoral head size on the wear of metal on metal total hip replacements under adverse edge-loading conditions. J Biomed Mater Res B 2013;101:213-222.

37. Drummond J, Tran P, Fary C. Metal-on-metal hip arthroplasty: a review of adverse reactions and patient management. J Funct Biomater 2015;6:486-499.

38. Boutilin P. Alumina and its use in surgery of the hip. Experimental study. Presse Med 1971;79:639-640 [Article in French].

39. 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;214:331-347.

40. Oonishi H, Clarke IC, Good V, Amino H, Ueno M. Alumina hip joints characterized by run-in wear and steady-state wear to 14 million cycles in hip-simulator model. J Biomed Mater Res A 2004;70:523-532.

41. Hannevouche D, Hamadouche M, Nizard R, et al. Ceramics in total hip replacement. Clin Orthop Relat Res 2005;430:62-71.

42. D’Antonio JA, Sutton K. Ceramic materials as bearing surfaces for total hip arthroplasty. J Am Acad Orthop Surg 2009;17:63-68.

43. Massin P, Lopes R, Masson B, Mainard D; French Hip & Knee Society (SFHG). Does Biolox Delta ceramic reduce the rate of component fractures in total hip replacement? Orthop Traumatol Surg Res 2014;100:S317-S321.

44. Lee YK, Ha YC, Yoo JJ, et al. Alumina-on-alumina total hip arthroplasty: a concise follow-up, at a minimum of ten years, of a previous report. J Bone Joint Surg [Am] 2010;92-A:1755-1779.

45. D’Antonio JA, Capello WN, Naughton M. Ceramic bearings for total hip arthroplasty have high survivorship at 10 years. Clin Orthop Relat Res 2012;470:373-381.

46. Patsatodis GE, Papadopoulos PP, Papavasiliou KA, et al. Primary cementless total hip arthroplasty with an alumina ceramic-on-ceramic bearing: results after a minimum of twenty years of follow-up. J Bone Joint Surg [Am] 2010;92-A:639-644.

47. Finkbone PR, Severson EP, Cabanela ME, Trousdale RT. Ceramic-on-ceramic total hip arthroplasty in patients younger than 20 years. J Arthroplasty 2012;27:213-219.

48. Byun JW, Yoon TR, Park KS, Seon JK. Third-generation ceramic-on-ceramic total hip arthroplasty in patients younger than 30 years with osteonecrosis of femoral head. J Arthroplasty 2012;27:1337-1343.

49. Al-Hajjar M, Fisher J, Hardaker C, Kurring G, Thompson J, Williams S. Wear of large diameter ceramic-on-ceramic bearings in total hip replacements under edge-loading conditions. 60th Annual Meeting of the Orthopaedic Research Society. New Orleans: 15-18 March 2014; http://www.aor.org/Transactions/60/1818.pdf (date last accessed 28 January 2016).

50. Smith AJ, Dieppe P, Vernon K, Porter M, Blom AW; National Joint Registry of England and Wales. Failure rates of stemmed metal-on-metal hip replacements: analysis of data from the National Joint Registry of England and Wales. Lancet 2012;379:1199-1204.

51. Mai K, Veriotti C, Ezzi KA, et al. Incidence of “squeaking” after ceramic-on-ceramic total hip arthroplasty. Clin Orthop Relat Res 2010;468:413-417.

52. Stanat SJ, Capozzi JD. Squeaking in third- and fourth-generation ceramic-on-ceramic total hip arthroplasty: meta-analysis and systematic review. J Arthroplasty 2012;27:445-453.

53. 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;98:281-287.

54. Owen DH, Russell NC, Smith PN, Walter WL. An estimation of the incidence of squeaking and revision surgery for squeaking in ceramic-on-ceramic total hip replacement: a meta-analysis and report from the Australian Orthopaedic Association National Joint Registry. Bone Joint J 2014;96-B:181-187.

55. Firkins PJ, Tipper JL, Ingham E, et al. A novel low wearing differential hardness, ceramic-on-metal hip joint prosthesis. J Biomech 2001;34:1291-1298.

56. Yi Z, Bo Z, Bin SJ, et al. Clinical results and metal ion levels after ceramic-on-metal total hip arthroplasty: a mean 50-month prospective single-center study. J Arthroplasty 2015;28:50883-540916(15)00848-7.

57. Schouten R, Malone AA, Tiffen C, Frampton CM, Hooper G. A prospective, randomised controlled trial comparing ceramic-on-metal and metal-on-metal bearing surfaces in total hip replacement. J Bone Joint Surg [Br] 2012;94-B:1462-1467.

58. Rajpuria A, Kendoff D, Board TN. The current state of bearing surfaces in total hip replacement. J Bone Joint Surg [Am] 2014;96-B:147-156.

59. Migaud H, Putman S, Combes A, et al. Metal-on-metal bearing: is this the end of the line? we do not think so. JSS 2012;8:252-259.

60. Silesen NH, Greene ME, Nebergall AK, et al. Three year RSA evaluation of vitamin E diffused highly cross-linked polyethylene liners and cup stability. J Arthroplasty 2015;30:1260-1264.