Recent Update
Clinics in Orthopedic Surgery 2014;6:110-116 • http://dx.doi.org/10.4055/cios.2014.6.1.110

Future Bearing Surfaces in Total Hip Arthroplasty

Jun-Dong Chang, MD

Arthroplasty Center, Department of Orthopaedic Surgery, Hallym University Dongtan Sacred Heart Hospital, Hallym University College of Medicine, Hwaseong, Korea

One of the most important issues in the modern total hip arthroplasty (THA) is the bearing surface. Extensive research on bearing surfaces is being conducted to seek an ideal bearing surface for THA. The ideal bearing surface for THA should have superior wear characteristics and should be durable, bio-inert, cost-effective, and easy to implant. However, bearing surfaces that are currently being implemented do not completely fulfill these requirements, especially for young individuals for whom implant longevity is paramount. Even though various new bearing surfaces have been investigated, research is still ongoing, and only short-term results have been reported from clinical trials. Future bearing surfaces can be developed in the following ways: (1) change in design, (2) further improvement of polyethylene, (3) surface modification of the metal, (4) improvement in the ceramic, and (5) use of alternative, new materials. One way to reduce wear and impingement in THA is to make changes in its design by using a large femoral head, a monobloc metal shell with preassembled ceramic liner, dual mobility cups, a combination of different bearing surfaces, etc. Polyethylene has improved over time with the development of highly crosslinked polyethylene. Further improvements can be made by reinforcing it with vitamin E or multiwalled carbon nanotubes and by performing a surface modification with a biomembrane. Surface modifications with titanium nitride or titanium niobium nitride are implemented to try to improve the metal bearings. The advance to the fourth generation ceramics has shown relatively promising results, even in young patients. Nevertheless, further improvement is required to reduce fragility and squeaking. Alternative materials like diamond coatings on surfaces, carbon based composite materials, oxidized zirconium, silicon nitride, and sapphire are being sought. However, long-term studies are necessary to confirm the efficacy of these surfaces after enhancements have been made with regard to fixation technique and implant quality.

Keywords: *Hip, Arthroplasty, Bearing surface, Wear*

Since the advent of low friction arthroplasty by Sir John Charnley, total hip arthroplasty (THA) has been proven to be an effective treatment for advanced hip disease. There has been a rise in the number of cases of THA, particularly in younger, active individuals over the past decade. Therefore, the search for an ideal bearing surface, which is important for the longevity of THA, is receiving more attention. The bearing surface should have superior wear characteristics and should be durable, bio-inert, cost-effective, and easy to implant.

The goal of developing alternate bearing surfaces has been to create a joint with decreased friction and wear rates but with increased strength. However, there is an ongoing debate regarding alternative bearing surfaces for THA. Despite all of the efforts to create an ideal bearing surface, every alternative has its own set of advantages and disadvantages that must be weighed in determining the optimal articulation. Moreover, higher failure rates in young patients justify plenty of caution in spite of significant improvements in the quality of bearing surfaces. Thus, ideal bearing surfaces for THA are still being continuously sought.

Future bearing surfaces can be developed by changing the design, improving the polyethylene, modifying

Received June 25, 2013; Accepted July 16, 2013
Correspondence to: Jun-Dong Chang, MD
Arthroplasty Center, Hallym University Dongtan Sacred Heart Hospital, Hallym University College of Medicine, 7 Keunjaebong-gil, Hwaseong 445-170, Korea
Tel: +82-31-8086-2411, Fax: +82-31-8086-2429
E-mail: jdchangos@gmail.com

the metal surface, improving the ceramic, or using an alternative new material. Although research and short-term clinical trials have generated optimistic results, much still needs to be learned with respect to the correct indications and long-term clinical results of these bearings. This article presents the various options for bearing surfaces in research or clinical trials that will help us develop an ideal bearing surface in the future.

BEARING SURFACES IN RESEARCH OR CLINICAL TRIALS

Change in Design

Larger femoral head

Sir John Charnley had advocated the use of small femoral heads based on the principle of low friction arthroplasty. However the current trend has shifted to the use of large femoral heads. Femoral head size of 32 mm or more provide an increase in range of motion and reduced dislocation rates[1] by decreasing impingement and increasing the jump-arm distance.

Monobloc metal shell with preassembled ceramic liner

Cementless acetabular cup with a preassembled delta ceramic liner allows optimization of the head-to-cup ratio, allowing the use of larger heads in a small diameter acetabulum. It thus permits increased range of motion and stability in young, active, and short Asian patients. With optimally placed components, the risk of dislocation is extremely low.[2] However, the acetabular component, being a monobloc system, has significant technical considerations.[2]

Dual mobility cup

The dual mobility cup was first described in France by Bousquet in 1976. This design combines both Charley's low friction principle of using a small femoral head that articulates against polyethylene to reduce wear and the Mckee-Farrar theory of using a larger head to enhance stability. This design has a small, inner constrained articulation between the femoral head and the polyethylene insert and a large, outer unconstrained articulation between the insert and the polished inner surface of the metal shell.[3,4] The small contact area of the inner articulation has low friction with most movement occurring there. With increasing motion, the femoral neck eventually contacts the polyethylene insert rim driving the outer articulation. The polyethylene insert effectively creates a large diameter head with a large jump distance to stabilize the construct. Since the outer articulation is not retentive, no distraction forces are transmitted to the metal cup, minimizing loosening potential. This implant is also an attractive option in challenging situations of unstable total hip arthroplasties.[4]

Ceramic on metal

A mixture of different hard bearing surfaces has created a novel option: the ceramic on metal (CoM) coupling (hard on hard), in which a ceramic femoral head articulates with a metal acetabular insert. This coupling was designed with the expectation of having the advantages of a lower risk of both squeaking and component fracture compared to ceramic-on-ceramic (CoC) couplings and reduced acetabular wear and metal debris production compared to metal-on-metal (MoM) bearings. A combination that limits metallic wear would be advantageous given the increasing recognition of adverse local tissue reactions and ongoing concerns surrounding systemic exposure to metal ions. CoM bearings have shown reduced wear relative to MoM bearings under standard and adverse clinically relevant simulator conditions.[5] The *in vivo* studies on the use of CoM bearings have shown conflicting results. Isaac et al.[6] observed that CoM bearings produce lower levels of metal ions than comparable MoM bearings do, and two retrieved components exhibited only cosmetic damage. A prospective, randomized controlled trial states that CoM and MoM couplings are associated with an equivalent increase in serum cobalt and chromium levels and comparable functional outcome scores at six and twelve months of follow-up.[7]

Further Improvement of Polyethylene

Evolution of highly crosslinked polyethylene

Highly crosslinked polyethylene (HXLPE) was developed in the 1990s to reduce poly wear and subsequent osteolysis.[8] However gamma irradiation cross-linking of polyethylene leads to formation of free radicals and oxidation products causing chain scission and a decrease in molecular weight of polyethylene, reducing its mechanical properties and accelerating wear. There are various products of HXLPE according to the irradiation dosage and the method of free radical stabilization. Alternate stabilization strategies are under development such as the administration of nitroxide-TEMPO (2,2,6,6-tetramethylpiperidine-1-oxyl),[9] hindered phenol antioxidant (HPAO),[10] or anthocyanin extracts.[11] The nitroxides in nitroxide-TEMPO are stable organic compounds which react with free alkyl radicals in polyethylene and do not alter cross link density.[9] The phenoxy radicals in HPAO stabilize the free alkyl radicals in the same manner. However, the cyto-compatibility of these compounds still needs to be established.[12]

The antioxidant anthocyanin is freely available in plants, flowers, and fruits like grapes and berries and is observed to have antioxidant properties four times that of vitamin E. Anthocyanin-doped, ultra-high molecular weight polyethylene (UHMWPE) is already under production.

Vitamin E stabilized polyethylene

The stabilization of radiation cross-linked UHMWPEs by adding the antioxidant vitamin E was developed to obtain oxidation resistance with improved fatigue strength by avoiding postirradiation melting. Postirradiation melting recombines free radicals but reduces the fatigue resistance of polyethylene. Vitamin E improves oxidation resistance of irradiated UHMWPE and maintains its fatigue strength. Blending and diffusion are two common methods used to incorporate vitamin E into UHMWPE. Blending involves mixing vitamin E before compression molding and cross-linking, thus achieving a uniform distribution of vitamin E. However, as some loss of vitamin E can occur after molding, radiation cross-linking, and sterilization, less vitamin E is then available for oxidation stabilization. Diffusion involves adding vitamin E after molding and radiation cross-linking. In diffusion, since there is no loss of vitamin E after radiation and cross-linking, more vitamin E is available for oxidation stabilization. However, the physical infusion of vitamin E can result in a non-uniform distribution within the polyethylene matrix, which can cause uneven mechanical properties. In simulator studies, vitamin E-incorporated polyethylene exhibited low wear and high oxidation strength.[13,14] Ten retrievals of vitamin E doped HXLPE have shown little to no oxidation with reduced free radical content at 0.1 to 19.5 months of follow-up.[15] Long-term studies are required to establish the effectiveness of vitamin E as an effective anti-oxidant *in vivo*.[16]

Multiwalled carbon nanotube-reinforced polyethylene

Multiwalled nanotubes are multiple concentric nanotubes precisely nested within one another. Chemically treated carbon nanotubes are mixed with UHMWPE via the ball milling process. An addition of 1 weight % multiwalled carbon nanotubes (MWCNT) revealed an increase of 150% in strain energy density, 140% in ductility, and up to 25% in tensile strength compared to pure UHMWPE.[17] Reinforcement of UHMWPE by adding MWCNT allows the improvement of mechanical characteristics and superior wear behavior (decreased wear volume and wear coefficient)[18] compared to that of UHMWPE and the improvement of cyto-compatibility comparable to that of UHMWPE. However few animal studies have observed the adverse effects of MWCNT on the lung, liver, and renal tissues.

Surface modification of polyethylene with biomembrane-mimic polymers

In natural synovial joints under physiological conditions, fluid film lubrication by the hydrated intermediate layer is essential for the smooth motion of joints. Surface modification is therefore important for the improvement of bearing materials. Poly(2-methacryloyloxyethyl phosphorylcholine) (PMPC) is a biomaterial which mimics the neutral phospholipids of cell membranes. PMPC polymers are one of the most common biocompatible and hydrophilic polymers studied and are now clinically used on the surfaces of intravascular stents, soft contact lenses, and artificial lungs and heart under the authorization of the US Food and Drug Administration. Surface modification by grafting PMPC onto the polyethylene surface may realize ideal hydrophilicity and lubricity resembling those of the physiologic joint surfaces. PMPC is grafted with the polyethylene membrane using photo-induced polymerization.[19] In hip simulator studies,[20,21] it is observed that PMPC grafting decreased frictional torque and dramatically reduced wear regardless of cross-linking of polyethylene liners or of difference in femoral head materials (ceramic or cobalt-chromium [CoCr]).

Surface Modification of Metal

Titanium nitride

This material is extremely hard and is used as a coating to improve the substrate's surface properties. Titanium nitride (TiN) ceramic coatings are prepared via physical vapor deposition (PVD) and have shown good *in vitro* results.[22,23] Analysis of a well-functioning implant,[24] retrieved postmortem from a low demand patient 1 year after total hip arthroplasty, revealed that wear debris, as delaminated surface asperities, can originate from a TiN coated femoral head and can manifest as adhesive wear on the articular surface. Raimondi and Pietrabissa[25] retrieved four implants at two to eight years of follow-up and argued that TiN-coated titanium alloy femoral heads were inadequate in the task of resisting *in vivo* third-body wear mechanisms.

Titanium niobium nitride

In a comparative study[26] TiN, titanium niobium nitride (TiNbN), and titanium carbonitride (TiCN) were deposited on stainless steel substrates, and it was observed that the three coatings have similar surface properties and are not cytotoxic. However, TiNbN seems to have the best tribological performance in the presence of albumin (a major protein in the periprosthetic fluid). The modification of implant alloys by the TiNbN coatings is carried out with the PVD arc-process. TiNbN gives a hard, smooth, low friction, wettable surface which when combined (TiNbN on TiNbN) allows for gaining fluid film lubrication. These properties are postulated to reduce wear and hence lower the release of Cr and Co ions *in vivo* at up to 8 years of follow-up.[27)] Bongaerts et al.[28)] observed reduced metal ion levels at two years of follow-up relative to MoM implants.

Further Improvement in Ceramic

In 1970, the first generation ceramic (alumina on alumina) was first used by Boutin. This evolved to the present fourth generation ceramic using nano-sized yttria-stabilised zirconia particles (25%) which are dispersed in the alumina matrix (74%) along with strontium (1%) in the form of a platelet to inhibit crack propagation and thus provide more strength.[29)] However, further improvement is required in terms of concerns of the fragility and squeaking.[30)] The high cost of ceramic-ceramic as a bearing surface also needs to be addressed.

Alternative New Materials

Diamond-like carbon films

These are favored for wear components because of their superior tribological and mechanical properties, biocompatibility, and inertness. The deposition of diamond coating is done via the filtered pulsed plasma arc discharge (FPAD) method. Initially, diamond-like carbon (DLC) coatings on titanium aluminium vanadium (TiAlV) femoral heads were used against a polyethylene counterpart. An *in vivo* study[31)] observed that 46% of the 101 diamond-like amorphous carbon-coated TiAlV heads sliding against a polyethylene counterpart were revised due to aseptic loosening at 8.5 years of follow-up. Retrieved femoral heads showed numerous pits and mass spots of local coating delamination and crevice corrosion. A simulator study[32)] compared the wear rate of metal/UHMWPE, metal/metal, and amorphous diamond/amorphous diamond and found them to be 50–100 mm^3/yr, 5–10 mm^3/yr, and 0.001 mm^3/yr, respectively. Thomas et al.,[33)] in a recent *in vitro* study on the effect of particle size on macrophages responses to nano-diamond wear debris, performed analyses of cell proliferation, cell viability, apoptosis, phagocytosis, and gene expression of pro-inflammatory cytokines and chemokines concluded that there is no potential inflammation due to the size effect ranging from 6 nm to 500 nm. Probably in the future, amorphous diamond/amorphous diamond coatings on cobalt chromium molybdenum (CoCrMo) may show promising results.

Carbon based composite materials

Carbon based composite materials have the potential to provide low wear rates and small, chemically inert, and less biologically active wear particles. The carbon materials studied are HMU-CVD, SMS-CVD, and P25-CVD. The HMU-CVD, SMS-CVD, and P25-CVD have a common matrix derived by chemical vapor deposition (CVD) of methane, but have a difference in fiber type. High modulus (HMU) and standard modulus (SMS) are polyacrylnitrile-based carbon fibers, while P25 is derived from mesophase pitch. They were observed to have lower wear rates than UHMWPE and to be less cytotoxic compared to poly and metal debris.[34)] P25-CVD had the lowest wear factor and produced very small debris that had minimal cytotoxic effects on L929 fibroblasts and U937 macrophage-like cells *in vitro*. Carbon-carbon composites such as P25-CVD may be important in the development of next-generation implants with low wear rates and reduced cytotoxic potential.

Oxidised zirconium

This material is produced by thermally-driven oxygen diffusion that transforms metallic zirconium alloy surface into a durable, low-friction oxide. This oxidized layer is not a ceramic coating but rather is a transformation of the surface that is 5 to 10 um thick. The oxidized layer is much harder and more scratch resistant than the untreated alloy. In a simulator study[35)] it was observed that smooth oxidised zirconium (oxinium) heads produced 45% less wear than did smooth CoCr heads, and, when the heads were roughened, the difference was much greater, with oxinium producing 61% less wear. Lewis et al.[36)] compared 50 CoCr and 50 oxinium heads and observed the clinical outcome to be equivalent at 2 years of follow-up. However, retrieved femoral oxinium heads have demonstrated loss of the oxinium layer with exposure of the underlying substrate with extensive damage to the polyethylene.[37)]

Silicon nitride

Silicon nitride is a non-oxide ceramic and is used in spinal fusion implants, maxillofacial reconstruction, surgical plates and screws. It is biocompatible, has high wear resistance and good osteo-conductive properties, inhibits biofilm formation and bacterial colonization, and is semi-radiolucent. The bearing surface can be fabricated from silicon nitride (Si3N4) powder. This has a high wear resistance, superior fracture toughness and flexural strength, and a low coefficient of friction of 0.001.[38)] Mechanical testing showed that Si3N4 had improved fracture toughness and fracture strength over modern alumina (Al2O3) ceramic. When tested with Si3N4 cups in a hip simulator, both CoCr and Si3N4 femoral heads produced low wear rates that were comparable to Al2O3-Al2O3 bearings in THA. The wear particles of silicon nitride are predicted to slowly dissolve in polar fluids, and they therefore have the potential to be resorbed *in vivo*, potentially reducing the risk of aseptic loosening.[39] In February 2011, the first silicon nitride total hip joint was implanted. Silicon nitride may allow improved THA bearings that combine the reliability of metal femoral heads with the low wear advantage of ceramics.

Sapphire

This material is aluminum oxide in the purest form with no porosity or grain boundaries. The sapphire friction pairs are made from highly purified materials with the crystals grown at 2,100°C in a vacuum. Under such conditions, additional purification of the material takes place and the content of the main substance (aluminium oxide) achieved is 99.99%. The use of sapphire as a friction bearing couple was studied by the Ukrainian Academy of Medical Sciences, Kharkov. They observed that the contacting surfaces of the sapphire friction pairs have a rather low and stable friction coefficient (0.05–0.10) as well as an extraordinarily high wear capacity.[40] They found sapphire to be biocompatible, having a low coefficient of friction and being inert and available at a low cost. Sapphire heads implanted in 5 patients have shown no complications for 5 years. The decreased friction and wear in combination with high biochemical inertness, biocompatibility, and low cost make the sapphire friction pair attractive for endoprostheses in the future.

CONCLUSIONS

There have been various trials in the history of THA for its longevity and survival. However, not all the new developments or trials in THA guaranteed promising results. As we have heard, “change is one thing, progress is another.” Nevertheless, the endeavor to search for “the real gold” for bearing surfaces should be continued for more promising results of THA. To confirm the efficacy of the new bearing surface, clinical studies with the long-term follow-up are essential.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

REFERENCES

1. Howie DW, Holubowycz OT, Middleton R; Large Articulation Study Group. Large femoral heads decrease the incidence of dislocation after total hip arthroplasty: a randomized controlled trial. J Bone Joint Surg Am. 2012;94(12):1095-102.
2. Dower B, Grobler G, Nortje M, Reid C. Deltamotion. Bone Joint J. 2013;95(Suppl 14):54.
3. Vielpeau C, Lebel B, Ardouin L, Burdin G, Lautridou C. The dual mobility socket concept: experience with 668 cases. Int Orthop. 2011;35(2):225-30.
4. Guyen O, Pibarot V, Vaz G, Chevillotte C, Bejui-Hugues J. Use of a dual mobility socket to manage total hip arthroplasty instability. Clin Orthop Relat Res. 2009;467(2):465-72.
5. Williams S, Al-Hajjar M, Isaac GH, Fisher J. Comparison of ceramic-on-metal and metal-on-metal hip prostheses under adverse conditions. J Biomed Mater Res B Appl Biomater. 2013;101(5):770-5.
6. Isaac GH, Brockett C, Breckon A, et al. Ceramic-on-metal bearings in total hip replacement: whole blood metal ion levels and analysis of retrieved components. J Bone Joint Surg Br. 2009;91(9):1134-41.
7. 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(11):1462-7.
8. Beksac B, Salas A, Gonzalez Della Valle A, Salvati EA. Wear is reduced in THA performed with highly cross-linked polyethylene. Clin Orthop Relat Res. 2009;467(7):1765-72.
9. Chumakov M, Silverman J, AI-Sheikhly M. Nitroxides as radical scavengers in UHMWPE. In: The 4th UHMWPE International Meeting; 2009 Sep 16-18; Torino, Italy.
10. King R, Narayan VS, Ernsberger C. Characterisation of gamma-irradiated UHMWPE stabilized with a Hindered-Phenol antioxidant. In: The 55th Annual Meeting of the Orthopaedic Research Society; 2009 Feb 22-24; Las Vegas, NV, USA.
11. He S, Le KP, Blitz JW. Anthocyanin doped UHMWPE: oxidation, wear and mechanical properties. In: The 55th

Annual Meeting of the Orthopaedic Research Society; 2009 Feb 22-24; Las Vegas, NV, USA.

12. Bladen CL, Tzu-Yin L, Fisher J, Tipper JL. In vitro analysis of the cytotoxic and anti-inflammatory effects of antioxidant compounds used as additives in ultra high-molecular weight polyethylene in total joint replacement components. J Biomed Mater Res B Appl Biomater. 2013;101(3):407-13.

13. Micheli BR, Wannomae KK, Lozynsky AJ, Christensen SD, Muratoglu OK. Knee simulator wear of vitamin E stabilized irradiated ultrahigh molecular weight polyethylene. J Arthroplasty. 2012;27(1):95-104.

14. Oral E, Muratoglu OK. Vitamin E diffused, highly crosslinked UHMWPE: a review. Int Orthop. 2011;35(2):215-23.

15. Rowell SL, Micheli BR, Wannomae KK, Malchau H, Muratoglu OK. In vivo performance of highly cross-linked UHMWPE. In: The 5th UHMWPE International Meeting; 2011 Sep 22-23; Philadelphia, PA, USA.

16. van der Veen HC, van den Akker-Scheek I, Bulstra SK, van Raay JJ. Wear, bone density, functional outcome and survival in vitamin E-incorporated polyethylene cups in reversed hybrid total hip arthroplasty: design of a randomized controlled trial. BMC Musculoskelet Disord. 2012;13:178.

17. Ruan SL, Gao P, Yang XG, Yu TX. Toughening high performance ultrahigh molecular weight polyethylene using multiwalled carbon nanotubes. Polymer. 2003;44(19):5643-54.

18. Kanagaraj S, Mathew MT, Fonseca A, Oliveira MS, Simoes JA, Rocha LA. Tribological characterisation of carbon nanotubes/ultrahigh molecular weight polyethylene composites: the effect of sliding distance. Int J Surf Sci Eng. 2010;4(4-6):305-21.

19. Ishihara K, Iwasaki Y, Ebihara S, Shindo Y, Nakabayashi N. Photoinduced graft polymerization of 2-methacryloyloxyethyl phosphorylcholine on polyethylene membrane surface for obtaining blood cell adhesion resistance. Colloids Surf B Biointerfaces. 2000;18(3-4):325-35.

20. Kyomoto M, Moro T, Miyaji F, et al. Effects of mobility/immobility of surface modification by 2-methacryloyloxyethyl phosphorylcholine polymer on the durability of polyethylene for artificial joints. J Biomed Mater Res A. 2009;90(2):362-71.

21. Moro T, Kawaguchi H, Ishihara K, et al. Wear resistance of artificial hip joints with poly(2-methacryloyloxyethyl phosphorylcholine) grafted polyethylene: comparisons with the effect of polyethylene cross-linking and ceramic femoral heads. Biomaterials. 2009;30(16):2995-3001.

22. Pappas MJ, Makris G, Buechel FF. Titanium nitride ceramic film against polyethylene: a 48 million cycle wear test. Clin Orthop Relat Res. 1995;(317):64-70.

23. Lee SB, Choi JY, Park WW, et al. A study of TiN-coated metal-on-polymer bearing materials for hip prosthesis. Met Mater Int. 2010;16(4):679-86.

24. Harman MK, Banks SA, Hodge WA. Wear analysis of a retrieved hip implant with titanium nitride coating. J Arthroplasty. 1997;12(8):938-45.

25. Raimondi MT, Pietrabissa R. The in-vivo wear performance of prosthetic femoral heads with titanium nitride coating. Biomaterials. 2000;21(9):907-13.

26. Serro AP, Completo C, Colaco R, et al. A comparative study of titanium nitrides, TiN, TiNbN and TiCN, as coatings for biomedical applications. Surf Coatings Tech. 2009;203(24):3701-7.

27. Woodnutt D, Hamelynck K, Woering R. Low metal ion release in patients at up to 8 years following titanium niobium nitride (TiNbN) surface treated metal-on-metal hip arthroplasty. J Bone Joint Surg Br. 2012;94(Suppl XLI):140.

28. Bongaerts G, Jensen K, Denda A, Schneider S. Limited increase of metal ion concentration in patients with a ceramic coated surface replacement. Der Unfallchirurg. 2009;112 Suppl 1:13.

29. Chevillotte C, Pibarot V, Carret JP, Bejui-Hugues J, Guyen O. Nine years follow-up of 100 ceramic-on-ceramic total hip arthroplasty. Int Orthop. 2011;35(11):1599-604.

30. Porat M, Parvizi J, Sharkey PF, Berend KR, Lombardi AV Jr, Barrack RL. Causes of failure of ceramic-on-ceramic and metal-on-metal hip arthroplasties. Clin Orthop Relat Res. 2012;470(2):382-7.

31. Hauert R, Falub CV, Thorwarth G, et al. Retrospective lifetime estimation of failed and explanted diamond-like carbon coated hip joint balls. Acta Biomater. 2012;8(8):3170-6.

32. Lappalainen R, Selenius M, Anttila A, Konttinen YT, Santavirta SS. Reduction of wear in total hip replacement prostheses by amorphous diamond coatings. J Biomed Mater Res B Appl Biomater. 2003;66(1):410-3.

33. Thomas V, Halloran BA, Ambalavanan N, Catledge SA, Vohra YK. In vitro studies on the effect of particle size on macrophage responses to nanodiamond wear debris. Acta Biomater. 2012;8(5):1939-47.

34. Howling GI, Sakoda H, Antonarulrajah A, et al. Biological response to wear debris generated in carbon based composites as potential bearing surfaces for artificial hip joints. J Biomed Mater Res B Appl Biomater. 2003;67(2):758-64.

35. Good V, Ries M, Barrack RL, Widding K, Hunter G, Heuer D. Reduced wear with oxidized zirconium femoral heads. J Bone Joint Surg Am. 2003;85 Suppl 4:105-10.

36. Lewis P, Bogoch E, Olsen M, Schemitsch E, Waddell J. Com-

parison of mid-term clinical outcomes following primary total hip arthroplasty with oxinium versus cobalt chrome femoral heads. J Bone Joint Surg Br. 2010;92(Supp IV):524.

37. Jaffe WL, Strauss EJ, Cardinale M, Herrera L, Kummer FJ. Surface oxidized zirconium total hip arthroplasty head damage due to closed reduction effects on polyethylene wear. J Arthroplasty. 2009;24(6):898-902.

38. Bal BS, Khandkar A, Lakshminarayanan R, Clarke I, Hoffman AA, Rahaman MN. Fabrication and testing of silicon nitride bearings in total hip arthroplasty: winner of the 2007 "HAP" PAUL Award. J Arthroplasty. 2009;24(1):110-6.

39. Olofsson J, Grehk TM, Berlind T, Persson C, Jacobson S, Engqvist H. Evaluation of silicon nitride as a wear resistant and resorbable alternative for total hip joint replacement. Biomatter. 2012;2(2):94-102.

40. Mamalis AG, Ramsden JJ, Grabchenko AI, Lytvynov LA, Filipenko VA, Lavrynenko SN. A novel concept in for the manufacture of individual sapphire-metallic hip joint endoprostheses. J Biol Phys Chem. 2006;6(3):113-7.