Advantages and disadvantages of ceramic on ceramic total hip arthroplasty: A review

Jiri Gallo^a, Stuart Barry Goodman^b, Jiri Lostak^a, Martin Janout^a

Background. Ceramic on ceramic (COC) total hip arthroplasty (THA) was developed to reduce wear debris and accordingly, the occurrence of osteolysis and aseptic loosening especially in younger patients. Based on the excellent tribological behavior of current COC bearings and the relatively low biological activity of ceramic particles, significant improvement in survivorship of these implants is expected.

Methods. We used manual search to identify all relevant studies reporting clinical data on COC THAs in PubMed. The objective was to determine whether current COC THA offers a better clinical outcome and survivorship than non-COC THA.

Results. Studies with early generation ceramic bearings yielded 68% to 84% mean survivorship at 20 years follow-up which is comparable with the survivorship of non-COC THAs. Studies on current ceramic bearings report a 10-year revision-free interval of 92% to 99%. These outcomes are comparable to the survivorship of the best non-COC THAs. However, there are still concerns regarding fracture of sandwich ceramic liners, squeaking, and impingement of the femoral neck on the rim of the ceramic liner leading to chipping, especially in younger and physically active patients.

Conclusion. Current COC THA leads to equivalent but not improved survivorship at 10 years follow-up in comparison to the best non-COC THA. Based on this review, we recommend that surgeons weigh the potential advantages and disadvantages of current COC THA in comparison to other bearing surfaces when considering young very active patients who are candidates for THA.

Key words: total hip arthroplasty, ceramic on ceramic, revision free interval, survivorship, advantages, disadvantages, osteolysis, aseptic loosening

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^aDepartment of Orthopaedics, Faculty of Medicine and Dentistry, Palacky University Olomouc and University Hospital Olomouc, Czech Republic

^bDepartment of Orthopaedic Surgery, Stanford University Medical Center Outpatient Center, 450 Broadway St., M/C 6342, Redwood City, CA, USA, 94063

Corresponding author: Jiri Gallo, email: jiri.gallo@volny.cz

INTRODUCTION

Particle-induced periprosthetic osteolysis and aseptic loosening are major complications of total hip arthroplasty (THA). The current paradigm relates osteolysis and loosening of THA to the cellular host adverse reaction due to continuous particle delivery from artificial joint surfaces¹. As osteolysis is closely associated with the production of large quantities of polyethylene (PE) particles, one solution would be to exclude PE from bearing materials used in THA and replace it by much harder and wear-resistant materials. The history of the use of ceramic materials, their structures, and the clinical outcomes of THAs with ceramic-on-ceramic (COC) bearings are described in detail elsewhere².

Here, we focus on the current ceramic materials that are used in orthopaedic practice today. These are formed by fusion of microscopic grains of alumina (Al₂O₃) and/or zirconia (ZrO₂) ceramic powder into a solid phase (Table 1). The process of sintering is “hot isostatic pressing” requiring temperatures exceeding 1400 °C and pressures above 1000 Bars. After sintering, the components

are ground and polished to get the finest surface possible. The manufacturing of COC bearings for orthopaedics is under strict control (more than 50 checkpoints according to the declaration of CeramTech AG, Plochingen, Germany) and in accordance with international quality standards (ISO 6474).

Compared to other currently used bearing couples, modern COC bearings demonstrate the lowest wear rates both *in vitro* and *in vivo*. For this reason, excellent clinical performance can be expected. The aim of this paper is to review the advantages and disadvantages associated with current COC THA.

LITERATURE SEARCH

PubMed (1996-2011) was meticulously searched to detect studies reporting clinical outcomes for COC THA using the following keywords and their combinations: “total hip arthroplasty/replacement”, “ceramic”, “ceramic on ceramic”, “aseptic loosening”, “osteolysis”, and “complications”. The relevant data including ceramic material,

Table 1. Characteristics of ceramic materials used currently in total hip arthroplasty.

Type of ceramic	Grain size (µm)	Density (g/m ³)	Bending strength (MPa)	Fracture toughness (MPa·m ^{1/2})	Vickers hardness	Young's modulus (GPa)
Alumina (<i>BIOLOX FORTE</i>)	< 2	3.98	580	4	20	380
Zirconia	< 0.5	n.a.	> 900	8	12.5	210
ZTAMC (<i>BIOLOX DELTA</i>)	< 2	4.37	> 1380	6.5	19	> 350

ZTAMC – Zirconia-toughened alumina matrix composite; n.a.-not available. Sources: CeramTec AG, Plochingen, Germany

number of patients/hips, period of implantation, primary diagnosis, average age at the time of surgery, sex, mean follow-up, survivorship, revision rate and reasons for revision were extracted. In addition, the best available data for non-COC THA were searched for the same period using identical search strategy except the word “ceramic”. Finally, literature pertinent to material characteristics of COC THA was searched using Google.

ADVANTAGES OF CERAMIC-ON-CERAMIC THA

Tribological remarks

Current ceramics used for manufacturing bearing surfaces in THA exhibit outstanding tribological properties, the most important of which are **hardness and high degree of wetability**. Ceramic has a greater hardness than metal and can be polished to a much lower surface roughness while excellent wetability ensures that the synovial fluid is uniformly distributed between implant surfaces³. The former guarantees high resistance to major scratches and **undetectable wear rate**, while the latter facilitates fluid-film lubrication thus contributing to very low friction between articulating surfaces ($< 1.7 \times 10^{-7} \text{ mm}^3/\text{Nm}$) (ref.⁴).

The basic mechanism of wear in COC articulations is intergranular erosion followed by isolated grain pull-out³. In fact, hip simulator studies of current COC bearings have shown very low wear rates (less than 0.1 mm^3 per million cycles) (ref.⁵). However, measurement of retrieved ceramic implants revealed much higher wear rates than above ($\geq 1 \text{ mm}^3/\text{yr.}$) and a characteristic “ceramic” wear pattern was noted⁶⁻⁸. The reason for these differences could lie in different biomechanical conditions *in vitro* and *in vivo*, with the latter being exposed to edge loading, recurrent separation of bearing surfaces and even direct impingement of the ceramic implant on the neck of the stem, that increase the total wear of the implant *in vivo*. However, even under microseparation conditions, the wear rates of current alumina and ZTAMC ceramics are lower than highly cross-linked polyethylene (up to $1.8 \text{ mm}^3/\text{million cycles}$) (ref.⁷).

Size of ceramic particles

Ceramic wear particles are continually released into the effective joint space during each step similar to non-

COC THA. Depending on the mechanism of wear, ceramic particles are typically **generated in smaller numbers and with a bimodal size range** involving nanometer size particles (mean 24 nm; range 5 to 90 nm) and larger particles (mean 0.43 µm ; range 0.05 to 3.2 µm) probably associated with grain boundary fracture⁹⁻¹⁰. In addition, even larger ceramic particles are generated during gross damage (catastrophic failure) of the bearing surfaces (Fig. 1).

Fig. 1. Left hip revised due to catastrophic failure of ceramic liner (a); metallosis with gross fragments of broken ceramic liner (b).

Biological activity of ceramic particles

Prosthetic particles released from artificial joints stimulate periprosthetic cells to produce an inflammatory and pro-osteolytic environment leading eventually to alteration of local bone homeostasis in favour of bone resorption. Generally, the impact of particle load on the extension of bone defects depends at least on the size, amount, origin, and shape of the particles¹¹.

COC THAs exhibit very low ceramic wear rates and in addition, ceramic wear particles have much *lower specific and functional biological activity* than polyethylene particles¹²⁻¹³. Catelas et al. showed that polyethylene particles stimulated greater release of TNF- α when compared to alumina or zirconia¹⁴. Kubo et al. found much less intense histiocytic response around particles of alumina ceramics (3.9 μ m in diameter) than that of UHMWPE (11 μ m), stainless steel (3.9 μ m), and CoCr (3.9 μ m) in a rabbit model¹⁵. Bos et al. studied macrophages in the pseudo-

synovial membrane from well-fixated implants retrieved at autopsy and found the percentage of macrophages was higher in the polyethylene-on-ceramic and metal-on-polyethylene groups (40-60%) than in the ceramic-on-ceramic group (20-40%) (ref.¹⁶⁻¹⁷). On the other hand, at least one study comparing macrophage apoptosis as a result of stimulation by alumina, zirconia, and PE particles found the response to be size and concentration dependent, rather than particle composition dependent¹⁸. The overall impression is that ceramic particles are biologically inert, but if released in sufficient numbers (e.g. cases of neck impingement or third body wear), ceramic particles can produce osteolysis similar to that induced by PE particles. In comparable doses, however, the biologic response is less intense with ceramic versus PE particles.

From the above, it could be deduced that osteolysis and aseptic loosening will be obviated in patients with COC THA. Unfortunately, this is controversial because

Table 2. List of the selective studies reporting survivorship for COC and non-COC THAs; unfortunately the majority of retrieved studies have several inconsistencies in reporting (e.g. unclear number of patients and hips, survivorship without the Kaplan-Maier statistical analysis, unreported 95% confidence interval) precluding direct comparison in above terms.

Author	Bearing pair	Number of patients	Number of THAs	Period of implantation	Average age (yrs.)	Range from to (yrs.)	Follow-up term	Survivorship (%)	95% CI (confidence interval)
Milosev et al. ⁴⁸	M-M	591	640	1994-2002	57	18-80	10	91	88-95
Neumann et al. ⁴⁹	M-M	99	100	1995-1996	56.7	36-75	10	94	89-99
Migaud et al. ⁵⁰	M-M	30	39	1995-1998	39.8	23-49	12	100	NA
Neuerburg et al. ⁵¹	M-M	1121	1270	NA	NA	NA	10	90	86-94
Delaunay et al. ⁵²	M-M	73	83	1995-2004	40.7	23-49	10	100	89.6-100
Kim et al. ⁵³	C-HPE	71	73	2000-2002	45.5	20-50	8.5	100	98-100
Garavaglia et al. ⁵⁴	C-HPE	518	561	1996-1998	69.3	24-98	10	98.8*	97.4-99.5*
Grobler et al. ⁵⁵	M-HPE	93	100	1991-1993	54	24-71	10	100	NA
Zweymüller et al. ⁵⁶	C-P	365	376	1993-1994	62.8	20-83	10	99.3	96.9-99.8
Epinette et al. ⁵⁷	C-P	384	418	1989-1991	69.6	21-88	10	98.2	NA#
Kim et al. ⁵³	C-P	78	109	1991-1993	46.8	21-49	10	93.6	NA
Wroblewski et al. ⁵⁸	C-P	NA	3611	1962-2005	67	12-93	10	97.5*	97.0-98.0*
Chevillotte et al. ⁵⁹	C-C	92	100	1999-2000	52.3	20-73	9	95.8	NA
Murphy et al. ⁶⁰	C-C	173	194	1997-2003	49.9	18-76	9	96	91-100
Park et al. ⁶¹	C-C	90	102	1999-2002	39	18-66	9.6	95.3	89.5-100
Mesko et al. ⁶²	C-C	848	930	1996-2000	51.3	NA	10	96.8	94.6-98.1
Boyer et al. ²⁷	C-C	76	83	1993-2003	39	NA	10	92	NA##
Lee et al. ²⁸	C-C	84	100	NA	41	18-65	10	99	97-100
D'Antonio et al. ²⁶	C-C	189	216	NA	53.1	30-73	10.3	97.9	91.9-99.5
Kress et al. ²⁹	C-C	71	75	1997-1999	58	34-77	10.5	97	NA
Sugano et al. ⁶³	C-C	87	100	1996-1998	56	41-73	14	95.7	89.0-98.4

NA – not available, M-M – metal-on-metal, C-HPE – ceramic-on-highly cross-linked polyethylene, M-HPE – metal-on-highly cross-linked polyethylene, C-P – ceramic-on-conventional polyethylene, C-C – ceramic-on-ceramic, # – survivorship, calculated using revision for all causes at 10 years, was 98.24%±0.0167, ## – the 10-year overall survival rate, considering failure to be revision for any cause, was 92±11%, * – survival analysis with revision for a loose acetabular component as the end-point

Table 3. Summary for a review on ceramic on ceramic THA.

Parameter	Ceramic on Ceramic	Ceramic/Metal on Polyethylene	Metal on Metal
Wear rate	30.5±7 µm/y ⁶⁴	218.2±13.7 µm/y ⁶⁴	20–25µm/y ⁶⁵
Particle size	0.13–78 µm ⁶⁶	30 nm–10 µm ⁶⁷	30–100 nm ⁶⁸
Cellular response to wear particles	Low	High	High
Hypersensitivity induced by wear debris	No	No	Yes
Tissue necrosis, ALVAL	No or weak	Weak	High grade
Dislocation#	0.78%	0.80%	0.74%
Infection#	0.32%	0.49%	0.53%
Mechanical loosening#	0.39%	0.22%	0.20%
Revision#	1.02%	1.16%	1.12%
Noisy hip	Up to 33%	Rarely	Less frequent
Survivorship, 10 yrs. FU	99% (95% CI; 97–100%) ²⁸	95.6% (95% CI; 90.1–98.3%) ⁶⁹	95.4% (95% CI; 85.8–99.8%) ⁷⁰
Survivorship, 20 yrs. FU	84.4% (95% CI; 0.56–1.33) ²³	81.8% (95% CI; 79.0–84.6%)*	84% NA ⁷¹

– up to 2 years of follow-up⁷²; ALVAL – aseptic lymphocytic vasculitis-associated lesions; FU – follow-up; * – 22 y. survivorship of Lubinus SP II for all diagnoses and all reasons for revisions (Swedish Hip Arthroplasty Report 2008); NA – not available

Table 4. The incidence of squeaking (from the lowest to the highest incidence).

Published	Author	State	Ceramic material	Period of implantation	Number of patients	Number of THAs	Average age (yrs.)	Follow-up (yrs.)	Incidence of squeaking	Incidence of all noises
2010	Park et al. ⁶¹	South Korea	NA	1999-2002	90	102	39	9.6	0%	NA
2011	Sugano et al. ⁶³	Japan	BioloX forte	1996-1998	87	100	56	14	0%	0.01%
2007	Lusty et al. ⁷³	Australia	BioloX forte	1997-1999	283	301	58	7.6	0.3%	NA
2008	Capello et al. ⁷⁴	USA	BioloX forte	1996-1998	452	475	NA	8.3	0.8%	NA
2011	Mesko et al. ⁶²	USA	NA	1996-2000	848	930	51.3	10	0.97%	2.5%
2011	D'Antonio et al. ²⁶	USA	NA	1996	NA	144	53.1	10.3	1.4%	NA
2011	Schroder et al. ⁷⁵	USA	NA	2003-2006	317	375	54	3.0	1.9%	11.0%
2011	Cogan et al. ⁷⁶	France	NA	2003-2004	238	284	52.4	NA	2.6%	10.6%
2010	Restrepo et al. ⁴⁰	USA	NA	1998-2004	266	304	45.5	NA	2.7%	NA
2011	Sexton et al. ³⁷	Australia	NA	1997-2008	NA	2 406	NA	9.4	3.1%	NA
2009	Greene et al. ⁷⁷	USA	NA	2003-2005	97	103	52.6	4.2	4.9%	NA
2011	Chevillotte et al. ⁵⁹	France	BioloX forte	1999-2000	92	100	59	9	5.4%	NA
2009	Jarrett et al. ⁷⁸	USA	NA	2003-2005	143	159	52	1.8	10.7%	32.8%

NA – not available

several studies demonstrated periprosthetic osteolysis even in patients with current COC THA (ref.¹⁹⁻²⁰). The reason may lie in the multifactorial origin of osteolysis and aseptic loosening when particle related parameters play an important role but not the only pathway inducing these entities²¹. In addition, ceramic bearing surfaces are not the only source of prosthetic particles. In support of this is a histological study of pseudomembranes from loosened alumina cups that suggested that this “unexpected” osteolysis was probably due to metal or cement debris rather than alumina particles². Thus, in terms of biological activity of ceramic particles, the advantages clearly outweigh the disadvantages.

Clinical evidence for ceramic-on-ceramic THA

Assuming that COC bearings offer the lowest wear rates and that ceramic particles induce minimal adverse biological activity, do these facts result in overall improvement in survivorship of THA?

Recent systematic reviews on survivorship of hard-on-hard bearings in THA revealed *variable implant longevity and rates of complications in earlier studies* (survival rates of 73% to 100% at mean follow up ranging from 31 to 240 months) (ref.²²). Early generations of ceramic-on-ceramic implants were characterized by high failure rates as a result of both component fracture and loosening of the monolithic acetabular component. However, in a recent retrospective study, Petsatodis et al. reported a survivorship of 84.4% of cementless alumina COC prostheses at 20 years follow-up²³. Others have reported significant differences in survivorship of COC bearings depending on the type of prosthesis and its fixation, especially with respect to cementless and cemented cups²⁴⁻²⁵. Therefore, the survivorship and rate of complications of ceramic bearing surfaces depend not only on the period of implantation (and therefore the generation of ceramic material), but also on other important factors e.g. design of the prosthesis, surgical technique and the method of femoral and acetabular fixation².

The new generations of ceramic implants suggest more promising outcomes (Table 2), especially in young and active patients, with survivorship rates (free of revision) between 92% and 99% at ten years of follow-up²⁶⁻³⁰. However, these data are comparable but not better than the best outcomes for both metal-on-metal and metal/ceramic-on-polyethylene articulations (Table 2). In addition, the number of studies and length of follow-up for COC bearings are still insufficient compared to ceramic/metal-on-polyethylene THAs. Finally, the strength of evidence might be further compromised by methodological weaknesses as was reported for other clinical research in orthopaedics³¹.

As a result the conclusion is that use of highly wear resistant bearing surfaces does not automatically guarantee longer survivorship than the best non-COC THAs. The reason lies at least partially in the occurrence of other unrelated complications (e.g. deep sepsis, instability, periprosthetic fracture etc.) that require revision surgery and *that are not prevented by simple choice of bearing surface* (Table 3). Even aseptic loosening cannot be completely resolved using one specific bearing surface because of

its multifactorial etiology³². On the other hand, the rate of osteolysis was diminished as a direct consequence of using ceramic bearings. Taken together, combining the best design of THA with COC bearings might improve the long-term outcomes. However, this remains to be demonstrated in well-conducted multicentre studies and/or arthroplasty registries data.

DISADVANTAGES OF COC BEARINGS IN THA

Ceramic head and liner fractures

Ceramic head and liner fractures are associated with massive metallosis and exposure of the local tissues to particles of titanium or cobalt-chromium alloy from the metallic components (Fig. 2). Earlier generations of alumina ceramic heads had a reported risk for fracture between 0.26% and 13.4%, however for newer implants (BioloX Forte) the reported fracture rate is much lower at 0.004 to 0.015% (ref.³³). Representative data for BioloX Delta are not currently available.

The risk of ceramic liner fracture in new generation ceramic materials has been reported to be between 0% and 5.3%, with a higher incidence among sandwich-type

Fig. 2. Lymph node (a) and muscles (b) retrieved from surrounding of the catastrophically failed THA with large islands of metallic material (courtesy of Vlasta Ticha, MD, PhD, H&E stain 40x).

ceramic cups than 1-piece components. Szymanski et al. who reported 5.3% (7/132) of ceramic liner fractures (sandwich type implant) at a mean 32 months after the surgery also revealed clinical risk factors for fracture³⁴. These included excessive weight, advanced age, dislocation, prosthetic impingement, and increased postoperative hip offset. In an FDA multicenter study, new composite ceramic materials (BioloX Delta alumina-on-alumina ceramic; one-piece component) exhibited no ceramic fracture within 3 years of follow-up³⁵. However, these materials have a relatively short clinical history, so further monitoring is necessary.

Squeaking

Another concern remains squeaking of ceramic bearings. This potentially affects the patient's quality of life and survivorship of the implant due to revision of the squeaky hip. Noises emanating from ceramic bearings (usually clicking and squeaking) have been reported with rates that vary from 0% to 33% (Table 4).

Currently there are several theories on the origin of squeaking but the exact mechanism is still unclear, and is likely multifactorial. Some authors reported that squeaky hips are associated with younger active, heavier, and taller patients³⁶⁻³⁷. Parvizi et al. revealed an association with a particular prosthetic design that enabled neck impingement on the metallic rim of the cup^{38,39}. Similarly, Restrepo et al. found a clear relationship between the prevalence of squeaking and the type of femoral component implanted⁴⁰. Alternatively, there are studies that did not report any squeaky hips even after 10 years of follow-up (Table 4). Other explanations for COC squeaking include localized "striped" wear, changes of fluid film lubrication conditions and femoral head microseparation⁴¹⁻⁴². As a ceramic head passes over the wear stripe, it could generate a vibration and the metallic parts (femoral stem and acetabular shell) amplify this vibration by resonating, resulting in an audible sound. This explanation is consistent with the fact that COC squeaking does not occur until an average of fourteen to eighteen months after surgery. Finally, squeaking could be generated by the rolling/sliding motion of the femoral head inside the liner in the current generation of COC THAs (ref.⁴³). Manufacturers have introduced acetabular shells with different liner materials that are interchangeable, possibly leading to a diameter mismatch in some cases that allows a rolling/sliding mechanism. Regardless of which theory is plausible, noisy hips can occur in up to 33% of hips with COC bearings; fortunately clinically the problem is often minor in the majority of patients and revision surgery is indicated only occasionally.

Damage of the ceramic rim

Direct contact between the neck of the stem and the rim of the ceramic liner during range of motion can result in rim damage. Ceramic fragments can then impose themselves between the ceramic surfaces contributing to accelerated wear. Under some circumstances forceful impingement can even result in dislocation of THA. Stafford et al. revised 6 hips with COC THAs; three of which were

revised for impingement-related complications including recurrent dislocation⁴⁴.

Concerns related to revision of ceramic-on-ceramic THA

One important clinical question is how to identify impending catastrophic failure of COC THA because it can occur suddenly without prior symptoms. In addition, the majority of patients with current COC THA will experience asymptomatic ongoing generation of wear debris and low risk of head or liner fracture. Toni et al. recommended performing an X-ray/CT examination in patients with noisy COC THA to distinguish between snapping hips and hips with macro-damaged bearing surfaces⁴⁵. If the examination is negative then the authors recommend joint fluid aspiration to detect ceramic particles due to minor surface damage.

Another problem is the stable cup with a one-piece ceramic liner because it may be difficult to remove the ceramic liner from the metallic cup. The removal of a ceramic liner from the shell can be accomplished by a strong perpendicular impact to the rim of the shell, which might disrupt the press fit forces of the conical liner (personal communication with Karl Knahr). The inner surface of the shell must not be damaged during this impact to avoid the necessity of removal of the damaged shell. A special suction cup instrument has been developed to facilitate removal of ceramic liner out of the metal shell without damaging the metal. However, it is ineffective in firmly fixed liner.

Another important question relates to whether a new ceramic head should be implanted on a non-revised stem neck (trunion) after removal of the previous ceramic head. Potential damaged areas of the taper by forceful removal of the previous head may later serve as stress risers (Fig. 3) that can initiate and propagate a crack that ultimately leads to a fracture of the newly implanted head. When a metallic ball is implanted to replace a fractured ceramic head, care must be taken to remove all ceramic particles from the joint cavity because alumina particles remaining in the surrounding tissues could cause third body wear of the new metallic ball. In this situation, the ceramic par-

Fig. 3. Trunk of the stem can be damaged after forceful removal of the original head which could deform neck surface of the stem; these deformations could induce places of increased strains and stresses in conjunction with a new ceramic head; original situation after index surgery (a); placement of a new ceramic head on damaged neck of the stem (b)

ticles, which are harder than metal, might damage a metal head in a short time. This is why some specialists advise against the use of a metal head in the scenario of revision due to a fractured ceramic head/liner⁴⁶. Accordingly, only revision to COC or ceramic-on-polyethylene is recommended in this case. A special ceramic revision head system that consists of toughened dispersion ceramic ball along with titanium sleeve has been developed which allows the surgeon to retain the stem and use the original trunion (e.g. BIOLOX®OPTION; CeramTec, Germany). If the above-mentioned sleeve is not used, it is strongly recommended to exclude the possibility that the retained stem taper is damaged by close gross visual inspection⁴⁷.

CONCLUSION

The newest alumina/composite ceramic bearing surfaces have only negligible risk for fracture of the head and liner, and exhibit very low wear rates. The most recent ten-year follow-up studies have demonstrated comparable survivorship with current ceramic/metal-on-polyethylene and even metal-on-metal bearing couples. The most important current concerns about COC bearings are squeaking, and component impingement and micro-separation, increasing the risk of surface damage and premature prosthetic failure. Risk for fracture of ceramic sandwich-type liners also remains a subject of concern. From the foregoing, the advantages and disadvantages of current COC THA should be carefully considered in younger, more active patients.

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CONFLICT OF INTEREST STATEMENT

Author's conflict of interest disclosure: The authors stated that there are no conflicts of interest regarding the publication of this article.

REFERENCES

- Gallo J, Kaminek P, Ticha V, Rihakova P, Ditmar R. Particle disease. A comprehensive theory of periprosthetic osteolysis: a review. *Biomed Pap Med Fac Univ Palacky Olomouc Czech Repub* 2002;146(2):21-8.
- Hannouche D, Zaoui A, Zadegan F, Sedel L, Nizard R. Thirty years of experience with alumina-on-alumina bearings in total hip arthroplasty. *Int Orthop* 2011;35(2):207-13.
- Kurtz SM, Ong, K. Contemporary total hip arthroplasty: Hard-on-hard bearings and highly crosslinked UHMWPE. In: Kurtz SM, editor. *UHMWPE Biomaterials Handbook*. 2nd ed. Burlington, MA, USA: Academic Press (Elsevier);2009. p.55-79.
- Rainforth WM, Ma L. A study of BioloX (R) delta subject to water lubricated reciprocating wear. *Tribol Int* 2010;43(10):1872-81.
- Williams S, Schepers A, Isaac G, Hardaker C, Ingham E, van der Jagt D, Breckon A, Fisher J. The 2007 Otto Aufranc Award. Ceramic-on-metal hip arthroplasties: a comparative in vitro and in vivo study. *Clin Orthop Relat Res* 2007;465:23-32.
- 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. *J Bone Joint Surg Br* 2007;89(9):1158-64.
- Nevelos J, Ingham E, Doyle C, Streicher R, Nevelos A, Walter W, Fisher J. 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):793-5.
- Affatato S, Traina F, Toni A. Microseparation and stripe wear in alumina-on-alumina hip implants. *Int J Artif Organs* 2011;34(6):506-12.
- Tipper JL, Hattton A, Nevelos JE, Ingham E, Doyle C, Streicher R, Nevelos AB, Fisher J. Alumina-alumina artificial hip joints. Part II: characterisation of the wear debris from in vitro hip joint simulations. *Biomaterials* 2002;23(16):3441-8.
- Fisher J, Jin Z, Tipper J, Stone M, Ingham E. Tribology of alternative bearings. *Clin Orthop Relat Res* 2006;453:25-34.
- Catelas I, Jacobs JJ. Biologic activity of wear particles. *Instr Course Lect* 2010;59:3-16.
- Fisher J, Bell J, Barbour PS, Tipper JL, Matthews JB, Besong AA, Stone MH, Ingham E. A novel method for the prediction of functional biological activity of polyethylene wear debris. *Proc Inst Mech Eng H* 2001;215(2):127-32.
- 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.
- Catelas I, Huk OL, Petit A, Zukor DJ, Marchand R, Yahia L. Flow cytometric analysis of macrophage response to ceramic and polyethylene particles: effects of size, concentration, and composition. *J Biomed Mater Res* 1998;41(4):600-7.
- Kubo T, Sawada K, Hirakawa K, Shimizu C, Takamatsu T, Hirasawa Y. Histocyte reaction in rabbit femurs to UHMWPE, metal, and ceramic particles in different sizes. *J Biomed Mater Res* 1999;45(4):363-9.
- 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 Orthop Scand* 2001;72(4):335-42.
- Bos I. Tissue reactions around loosened hip joint endoprostheses. A histological study of secondary capsules and interface membranes. *Orthopade* 2001;30(11):881-9.
- Catelas I, Petit A, Zukor DJ, Marchand R, Yahia L, Huk OL. Induction of macrophage apoptosis by ceramic and polyethylene particles in vitro. *Biomaterials* 1999;20(7):625-30.
- Park YS, Hwang SK, Choy WS, Kim YS, Moon YW, Lim SJ. Ceramic failure after total hip arthroplasty with an alumina-on-alumina bearing. *J Bone Joint Surg Am* 2006;88(4):780-7.
- 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):2262-77.
- Sundfeldt M, Carlsson LV, Johansson CB, Thomsen P, Gretzer C. Aseptic loosening, not only a question of wear: a review of different theories. *Acta Orthop* 2006;77(2):177-97.
- Zywił MG, Sayeed SA, Johnson AJ, Schmalzried TP, Mont MA. Survival of hard-on-hard bearings in total hip arthroplasty: a systematic review. *Clin Orthop Relat Res* 2011;469(6):1536-46.
- Petsatodis GE, Papadopoulos PP, Papavasiliou KA, Hatzokos IG, Agathangelidis FG, Christodoulou AG. 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(3):639-44.
- Iwakiri K, Iwaki H, Minoda Y, Ohashi H, Takaoka K. Alumina inlay failure in cemented polyethylene-backed total hip arthroplasty. *Clin Orthop Relat Res* 2008;466(5):1186-92.
- 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):213-9.
- 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(2):373-81.
- Boyer P, Hutten D, Loriaut P, Lestrat V, Jeanrot C, Massin P. Is alumina-on-alumina ceramic bearings total hip replacement the right choice in patients younger than 50 years of age? A 7- to 15-year follow-up study. *Orthop Traumatol Surg Res* 2010;96(6):616-22.

28. Lee YK, Ha YC, Yoo JJ, Koo KH, Yoon KS, Kim HJ. 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(8):1715-9.
29. Kress AM, Schmidt R, Holzwarth U, Forst R, Mueller LA. Excellent results with cementless total hip arthroplasty and alumina-on-alumina pairing: minimum ten-year follow-up. *Int Orthop* 2011;35(2):195-200.
30. Jeffers JR, Walter WL. Ceramic-on-ceramic bearings in hip arthroplasty: state of the art and the future. *J Bone Joint Surg Br* 2012;94(6):735-45. Review.
31. van Oldenrijk J, Sierevelt IN, Schafoth MU, Poolman RW. Design considerations in implant-related randomized trials. *J Long Term Eff Med Implants* 2007;17(2):153-63.
32. 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.
33. Huet R, Sakona A, Kurtz SM. Strength and reliability of alumina ceramic femoral heads: Review of design, testing, and retrieval analysis. *J Mech Behav Biomed Mater* 2011;4(3):476-83.
34. Szymanski C, Gueriot S, Boniface O, Deladerriere JY, Luneau S, Maynou C. Sandwich type ceramic liner fracture rate with the Atlas III socket: A study of 144 primary total hip replacements at a mean 74months' follow-up. *Orthop Traumatol Surg Res* 2011;97(5):494-500.
35. Hamilton WG, McAuley JP, Dennis DA, Murphy JA, Blumenfeld TJ, Politi J. THA with Delta ceramic on ceramic: results of a multicenter investigational device exemption trial. *Clin Orthop Relat Res* 2010;468(2):358-66.
36. Walter WL, Waters TS, Gillies M, Donohoo S, Kurtz SM, Ranawat AS, Hozack WJ, Tuke MA. Squeaking hips. *J Bone Joint Surg Am* 2008;90 Suppl 4:102-11.
37. Sexton SA, Yeung E, Jackson MP, Rajaratnam S, Martell JM, Walter WL, Zicat BA, Walter WK. The role of patient factors and implant position in squeaking of ceramic-on-ceramic total hip replacements. *J Bone Joint Surg Br* 2011;93(4):439-42.
38. Parvizi J, Adeli B, Wong JC, Restrepo C, Rothman RH. A squeaky reputation: the problem may be design-dependent. *Clin Orthop Relat Res* 2011;469(6):1598-605.
39. 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(3):445-53. Epub 2011 Jun 14. Review.
40. Restrepo C, Post ZD, Kai B, Hozack WJ. The effect of stem design on the prevalence of squeaking following ceramic-on-ceramic bearing total hip arthroplasty. *J Bone Joint Surg Am* 2010;92(3):550-7.
41. Taylor S, Manley MT, Sutton K. The role of stripe wear in causing acoustic emissions from alumina ceramic-on-ceramic bearings. *J Arthroplasty* 2007;22(7 Suppl 3):47-51.
42. Glaser D, Komistek RD, Cates HE, Mahfouz MR. Clicking and squeaking: in vivo correlation of sound and separation for different bearing surfaces. *J Bone Joint Surg Am* 2008;90 Suppl 4:112-20.
43. Currier JH, Anderson DE, Van Citters DW. A proposed mechanism for squeaking of ceramic-on-ceramic hips. *Wear* 2010;269(11-12):782-9.
44. Stafford GH, Islam SU, Witt JD. Early to mid-term results of ceramic-on-ceramic total hip replacement: analysis of bearing-surface-related complications. *J Bone Joint Surg Br* 2011;93(8):1017-20.
45. Toni A, Traina F, Stea S, Sudanese A, Visentin M, Bordini B, Squarizoni S. Early diagnosis of ceramic liner fracture. Guidelines based on a twelve-year clinical experience. *J Bone Joint Surg Am* 2006;88 Suppl 4:55-63.
46. Pospischill M, Knahr K. Strategies for head and inlay exchange in revision hip arthroplasty. *Int Orthop* 2011;35(2):261-5.
47. Hannouche D, Delambre J, Zedegan 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):3322-7.
48. Milosev I, Trebse R, Kovac S, Cor A, Pisot V. Survivorship and retrieval analysis of Sikomet metal-on-metal total hip replacements at a mean of seven years. *J Bone Joint Surg Am* 2006;88(6):1173-82.
49. Neumann DR, Thaler C, Hitzl W, Huber M, Hofstadter T, Dorn U. Long-term results of a contemporary metal-on-metal total hip arthroplasty: a 10-year follow-up study. *J Arthroplasty* 2010;25(5):700-8.
50. Migaud H, Putman S, Krantz N, Vasseur L, Girard J. Cementless metal-on-metal versus ceramic-on-polyethylene hip arthroplasty in patients less than fifty years of age: a comparative study with twelve to fourteen-year follow-up. *J Bone Joint Surg Am* 2011;93 Suppl 2:137-42.
51. Neunerburg C, Impellizzeri F, Goldhahn J, Frey P, Naal FD, von Knoch M, Leunig M, von Knoch F. Survivorship of second-generation metal-on-metal primary total hip replacement. *Arch Orthop Trauma Surg* 2012;132(4):527-33.
52. Delaunay CP, Bonomet F, Clavert P, Laffargue P, Migaud H. THA using metal-on-metal articulation in active patients younger than 50 years. *Clin Orthop Relat Res* 2008;466(2):340-6.
53. Kim YH, Kim JS, Park JW, Joo JH. Comparison of total hip replacement with and without cement in patients younger than 50 years of age: the results at 18 years. *J Bone Joint Surg Br* 2011;93(4):449-55.
54. Garavaglia G, Lubbeke A, Barea C, Roussos C, Peter R, Hoffmeyer P. Ten-year results with the Morscher press-fit cup: an uncemented, non-modular, porous-coated cup inserted without screws. *Int Orthop* 2011;35(7):957-63.
55. Grobler GP, Learmonth ID, Bernstein BP, Dower BJ. Ten-year results of a press-fit, porous-coated acetabular component. *J Bone Joint Surg Br* 2005;87(6):786-9.
56. Zweymuller KA, Steindl M, Schwarzingner U. Good stability and minimal osteolysis with a biconical threaded cup at 10 years. *Clin Orthop Relat Res* 2007;463:128-37.
57. Epinette JA, Manley MT, D'Antonio JA, Edidin AA, Capello WN. A 10-year minimum follow-up of hydroxyapatite-coated threaded cups: clinical, radiographic and survivorship analyses with comparison to the literature. *J Arthroplasty* 2003;18(2):140-8.
58. Wroblewski BM, Siney PD, Fleming PA. Charnley low-friction arthroplasty: survival patterns to 38 years. *J Bone Joint Surg Br* 2007;89(8):1015-8.
59. Chevallotte 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.
60. Murphy SB, Ecker TM, Tannast M. Two- to 9-year clinical results of alumina ceramic-on-ceramic THA. *Clin Orthop Relat Res* 2006;453:97-102.
61. Park YS, Park SJ, Lim SJ. Ten-year results after cementless THA with a sandwich-type alumina ceramic bearing. *Orthopedics* 2010;33(11):796.
62. Mesko JW, D'Antonio JA, Capello WN, Bierbaum BE, Naughton M. Ceramic-on-ceramic hip outcome at a 5- to 10-year interval: has it lived up to its expectations? *J Arthroplasty* 2011;26(2):172-7.
63. Sugano N, Takao M, Sakai T, Nishii T, Miki H, Ohzono K. Eleven- to 14-year Follow-up Results of Cementless Total Hip Arthroplasty Using a Third-generation Alumina Ceramic-on-ceramic Bearing. *J Arthroplasty* 2012;27(5):736-41.
64. Amanatullah DF, Landa J, Strauss EJ, Garino JP, Kim SH, Di Cesare PE. Comparison of surgical outcomes and implant wear between ceramic-ceramic and ceramic-polyethylene articulations in total hip arthroplasty. *J Arthroplasty* 2011;26(6 Suppl):72-7.
65. Paleochorlidis IS, Badras LS, Skretas EF, Georgaklis VA, Karachalios TS, Malizos KN. Clinical outcome study and radiological findings of Zweymuller metal on metal total hip arthroplasty. a follow-up of 6 to 15 years. *Hip Int* 2009;19(4):301-8.
66. Santavirta S, Bohler M, Harris WH, Konttinen YT, Lappalainen R, Muratoglu O, Rieker C, Salzer M. Alternative materials to improve total hip replacement tribology. *Acta Orthop Scand* 2003;74(4):380-8.
67. Richards L, Brown C, Stone MH, Fisher J, Ingham E, Tipper JL. Identification of nanometre-sized ultra-high molecular weight polyethylene wear particles in samples retrieved in vivo. *J Bone Joint Surg Br* 2008;90(8):1106-13.
68. Catelas I, Wimmer MA. New insights into wear and biological effects of metal-on-metal bearings. *J Bone Joint Surg Am* 2011;93 Suppl 2:76-83.
69. Pieringer H, Auersperg V, Bohler N. Long-term results of the cementless ALLOCLASSIC hip arthroplasty system using a 28-mm ceramic head: with a retrospective comparison to a 32-mm head. *J Arthroplasty* 2006;21(7):967-74.
70. Shetty V, Shitole B, Shetty G, Thakur H, Bhandari M. Optimal bearing surfaces for total hip replacement in the young patient: a meta-analysis. *Int Orthop* 2011;35:1281-7.
71. Brown SR, Davies WA, DeHeer DH, Swanson AB. Long-term survival of McKee-Farrar total hip prostheses. *Clin Orthop Relat Res* 2002;402:157-63.

72. Bozic KJ, Ong K, Lau E, Kurtz SM, Vail TP, Rubash HE, Berry DJ. Risk of complication and revision total hip arthroplasty among Medicare patients with different bearing surfaces. *Clin Orthop Relat Res* 2010;468(9):2357-62.
73. 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):2676-83.
74. Capello WN, D'Antonio JA, Feinberg JR, Manley MT, Naughton M. Ceramic-on-ceramic total hip arthroplasty: update. *J Arthroplasty* 2008;23(7 Suppl):39-43.
75. Schroder D, Bornstein L, Bostrom MP, Nestor BJ, Padgett DE, Westrich GH. Ceramic-on-ceramic total hip arthroplasty: incidence of instability and noise. *Clin Orthop Relat Res* 2011;469(2):437-42.
76. Cogan A, Nizard R, Sedel L. Occurrence of noise in alumina-on-alumina total hip arthroplasty. A survey on 284 consecutive hips. *Orthop Traumatol Surg Res* 2011;97(2):206-10.
77. Greene JW, Malkani AL, Kolisek FR, Jessup NM, Baker DL. Ceramic-on-ceramic total hip arthroplasty. *J Arthroplasty* 2009;24(6 Suppl):15-8.
78. 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):1344-9.