*Acta Orthop. Belg.*, 2013, **79**, 181-190

*ORIGINAL STUDY*

# Alumina on alumina versus metal on conventional polyethylene : A randomized clinical trial with 9 to 15 years follow-up

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**We report the long-term results of a randomized clinical trial that compares, in total hip arthroplasty in a young population, metal-on-conventional polyethylene and alumina-on-alumina ceramic bearings. One hundred and forty hips in 116 patients were randomized. Re-operation, revision rate, clinical scores, and radiological signs of osteolysis and loosening were compared at average follow-up of 12.3 (9-15) years. At final FU, 107 hips were available for clinical evaluation. Eight (11.6%) revisions were performed in the polyethylene group versus 1 (1.4%) in the ceramic group (p = 0.017). All revisions in the polyethylene group were related to bearing wear : 4 for aseptic loosening with severe osteolysis, 1 for polyethylene induced compressive granulomatous tumor, and 3 for severe liner wear. The only revised case from the ceramic group was secondary to mechanical stem loosening. Mean annual polyethylene wear was 0.19 mm/year ; wear was not measurable in the ceramic group.**

**Our study confirms, in the long-term, the superiority of ceramic-on-ceramic pairing in comparison to metal-on-conventional polyethylene and supports their use in young, active patients.**

**Keywords** : hip arthroplasty, bearing surfaces, ceramic, polyethylene, wear, osteolysis.

*Author ML is consultant for Wright Medical and Biomet, and author PAV for Wright Medical, Biomet and Stryker.*
*The institution of one or more of the authors (ND, PL, ML and PAV) has received funding from Ceraver, Wright Medical, Biomet, Smith and Nephew, Stryker and Zimmer. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.*

## INTRODUCTION

Metal-on-conventional polyethylene (MoP) in total hip arthroplasty (THA), a bearing surface with good long-term results in elderly patients, has been established as the gold standard (*12*). However, conventional polyethylene (CPE) wear-related complications are the second most common reason for revision, as of 2006 (19.7% of all revisions in the USA) (*6*). Implant wear is a function of use, and younger patients normally have more active lifestyles and are thus at increasing risk of post-operative prosthetic failure due to polyethylene (PE) wear and secondary osteolysis (*1,8,19,24,28,31,40,45,46,56, 58*). Reduction of bearing wear is crucial and has stimulated the development of alternative bearing

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surfaces, such as alumina-on-alumina ceramic (CoC), metal-on-metal, and different types of highly cross-linked polyethylenes (XLPE).

CoC bearings have been in use since 1970 (*4*), with promising results in some patient cohorts (*16,33, 62,72,73*). The main advantages of CoC bearings are their favourable tribological properties (*41,54*), scratch resistance (*16,43*), decreased wear (*3,65,66*), and lower ceramic particle bioactivity (*9,10,42*) with lower risk of osteolysis and limited systemic effects (*11,16,44,50,53*). On the other hand, several potential disadvantages of CoC bearings have been observed : higher cost, risk of fracture (mean 0.006%) (*27*), diminished intra-operative versatility related to neck length and liner (no elevated lip), and squeaking (0% to 2.5%) (*13,60*).

To establish the true clinical value of CoC bearings, a randomized controlled trial (RCT) comparing their long-term results with gold standard bearings (CPE) was essential. In 1996, we undertook such a RCT (*67*). The primary outcome was to determine if CoC has a lower aseptic revision rate than MoP and, as secondary outcome, if CoC provide better functional scores. With short-term follow-up (mean 6.5 years) results were similar between groups (*67*). However, as expected, longer follow-up was needed to observe significant differences so in the present paper, we report the mean of 12.3 years FU of the same patient groups.

## MATERIALS AND METHODS

### Trial design

From 1996 to 2001, patients > 18 years old or < 70 years with degenerative hip joint disease who were candidates for THA, and without the following exclusion criterias : presence of an active infection, severe osteoporosis, non-cooperative patient, severe hip instability, pregnancy, and a measured acetabular diameter of less than 50 mm, were recruited by 3 orthopaedic surgeons. Participants were randomly assigned to MoP or CoC bearing surface group. A randomization table was created with Statgraphic Plus 2.2 software (Manugistics Inc., Rockville, USA). Randomization was revealed by the research nurse to the surgeon in the operating room. The patient was kept blinded to the implanted bearing surfaces until 12 months after surgery. For "intention-to-treat" analysis, clinical results from all available patients were taken into account.

### Power analysis

With an expected rate of loss to follow-up of 15%, an estimated sample size of 70 in each group was needed to provide a power of 80% to detect a clinically meaningful difference of 15% in revision rate with an alpha error of 0.05.

### Participants

One hundred and forty hips in 116 patients were randomized. Sixty nine hips in 58 patients received MoP (37 patients with unilateral MoP, 11 with bilateral MoP, and 10 with MoP on one side and CoC on the other side) and 71 hips in 68 patients received CoC (55 patients with unilateral CoC, 3 with bilateral CoC, and 10 with MoP on one side and CoC on the other side). The scientific and ethics committee approved the research protocol and all subjects gave written informed consent before participating in the study. Demographic characteristics of the enrolled patients are presented in Table I.

### Implants

The same hybrid THA was implanted in all patients (Ceraver Osteal, Roissy, France). The cemented femoral implant has a smooth titanium alloy (TiAl) surface covered by a layer of titanium oxide ($TiO_2$). It has a collar and a cervico-diaphyseal angle of 132°. The uncemented acetabular implant (Cerafit®) is made of titanium. Screw holes are available for supplementary primary fixation, and a titanium mesh covers the outer surface for secondary fixation (with current Cerafit implant, osseointegration surface has been replaced by a hydroxyapatite plasma spray coating). The bearing surfaces were either an alumina insert with an alumina femoral head of 32 mm for the CoC group, or a polyethylene insert (Chirulen 1020, sterilized with ethylene oxide in 1996 and 1997, and with gamma irradiation in argon from 1997 to 2001) with a 28-mm stainless steel femoral head for the MoP group. No liner had an elevated lip.

### Surgical technique

One dose of intravenous antibiotics was administered pre-operatively and continued for 24 hours post-operatively (cefazolin 1 g or clindamycin 600 mg every

Table I. — Demographic characteristics and differential diagnoses of the enrolled patients

| | MoP | CoC |
|---|---|---|
| Numbers randomized | 69 | 71 |
| Gender (ratio M/F) | 38/31 | 30/41 |
| Age (in years) | 56.8<br>(min 29, max 70, SD 10.7) | 54.9<br>(min 23, max 70, SD 12.5) |
| Side Right/Left | 38/31 | 38/33 |
| Weight (in Kg) | 73.5<br>(min 45, max 107, SD 12.6) | 77.4<br>(min 48, max 160, SD 21.5) |
| BMI | 27.3 | 28.2 |
| Height (in cm) | 167 | 168 |
| Diagnosis: | | |
| OA | 43 | 44 |
| AVN | 10 | 11 |
| DDH | 4 | 2 |
| Childhood pathology | 4 | 1 |
| Inflammatory diseases | 8 | 12 |

8 hours). An anterolateral approach (modified Hardinge) was taken in 122 hips (ND), and a posterior approach in the remaining 18 hips. The acetabular component was implanted according to a press fit technique with 2-mm under-reaming. Utilization of screws was left to the surgeon's discretion. The femoral canal was prepared with rasp only, and we attempted to insert the largest possible implant. The stem was cemented with low-viscosity cement (Simplex®, Stryker), according to a second-generation method (*47*).

**Clinical evaluation**

Clinical results were compared pre-operatively and at last follow-up using the Western Ontario and McMaster Universities Arthritis Index (WOMAC) (*2*) and the Merle d'Aubigné-Postel scale (PMA) (*17*), and University of California Los Angeles score (UCLA) were compared at last follow-up. As an "intention-to-treat" analysis, clinical results from all available patients were taken into account (excluding 7 early reoperation cases leading to discontinued intervention).

**Radiologic evaluation**

Antero-posterior radiographs of the pelvis and a cross-table lateral radiograph of the hip taken post-operatively and at last follow-up were analyzed. The selected radiographs were scanned with a high-resolution (300 dpi) optical scanner (Vidar VXR-12, Herndon, VA, USA) and analyzed with Imagika™ software (View Tech, CMC Corp., NJ, USA) (*29*). All radiographs were reviewed and measured by two assessors. The assessment of radiographs was not done blind because of the difference in density between stainless steal and alumina femoral heads. Description of radiolucent line and local osteolysis were done with the use of Gruen's zones for the femur (*35*) and Charnley-De Lee for the acetabulum (*22*). Radiolucent line was defined as a lucent area in close proximity to the implant either more than 2mm thickness or evolutive. Osteolysis was recorded for either cavitary defect (scalloping), or calcar resorption which seems not to be a consequence of calcar remodeling with the calcar becoming round and thinner. Implant stability was evaluated according to criteria described by Engh *et al* (*26*). Heterotopic ossification was recorded according to the Brooker *et al* classification (*7*). Linear head penetration of the acetabular liners was measured by changes in the vectorial distance between the cup and head centres (*64*) using Imagika software having 0.13mm mean measurement error (*68*). The vertical inclination of the acetabular component was measured by reference to a horizontal line between the teardrops ; its height was measured from the distance between the inferior border of the cup to the inter-teardrop line (*48*). Femoral and cup offset was evaluated by the perpendicular distance from the centre of

rotation of the femoral head to, respectively, the centre line of the femur's diaphysis and to the perpendicular line to the tear-drop line crossing the ipsilateral tear-drop *(49)*.

**Statistical analysis**

Continuous variables are presented as means ± SD, and categorical variables, as frequencies and percentages. For primary and secondary outcomes, the MoP and CoC groups were compared by Chi-square and t-tests for categorical and continuous variables respectively. Survival curves according to the Kaplan-Meier method are also presented. Additional analysis was undertaken in the MoP group on the relationship between different clinical outcomes and patient characteristics (such as age at surgery, weight, body mass index), and revisions and radiolucent lines were assessed by t-tests. Correlations were calculated between wear and continuous clinical outcomes. The Chi-square test analyzed the relationship between osteolysis and annual wear (categorized by 0.2 mm/year as threshold). Fisher's exact test was used instead of the Chi-square test when expected frequencies were too low. The significance level was defined as $p < 0.05$. For additional analysis, results with p-values between 0.05 and 0.20 are reported as possible trends, considering the study's limited power. Statistical analyses were performed with SPSS 20.0 software (SPSS Inc., Chicago, IL, USA).

## RESULTS

Of the 140 hips included in this study, 52 CoC and 55 MoP were available at last FU for clinical evaluation, with radiographic data on 42 CoC and 47 MoP (patients only reached by phone). Eleven CoC hips and 5 MoP hips were considered lost to FU (11.4%). No significant difference in patient demographics was found between patients lost to FU and available subjects ($p = 0.229$-$0.958$). Average FU was 12.3 years (minimum 9.0, maximum 15) for the MoP group, and 12.3 years (minimum 9.0, maximum 14.6) for the CoC group.

Aseptic revision rates between groups were significantly different : 8/69 (11.6%) in the MoP group (average revision time 10.8 years) versus 1/70 (1.4%) in the CoC group ($p = 0.017$) (see Kaplan-Meier chart, Fig. 1). Aseptic revision in the MoP group involved 3 cases of isolated severe liner wear > 3 mm, 3 femoral and 1 acetabular osteolyses leading to implant loosening, and 1 granulomatous pseudo-tumour causing crural nerve compression with associated femoral osteolysis. In the CoC group, the only revision was related to mechanical stem loosening at 8 years. In the MoP group, significant correlations were noted between revision and higher annual wear (0.30 mm/year versus 0.20 mm/year, $p = 0.009$), higher total linear wear (3.12 mm versus 2.26 mm, $p = 0.028$) and higher acetabular inclination (55.2° versus 46.7°, $p = 0.024$).

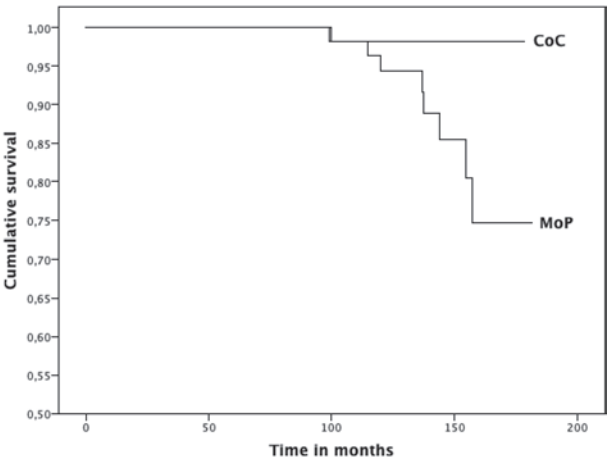


***Fig. 1.*** — Kaplan-Meier chart with aseptic loosening as endpoint.

Better clinical scores were obtained in the CoC group, but a significant difference was only found with UCLA score (5.6 versus 4.8, $p = 0.015$), a tendency was observed with the PMA scale (16.5 versus 15.5, $p = 0.068$) and no difference with the WOMAC scale (10.7 versus 16.6, $p = 0.10$). Although not significant, the MoP group tended to report higher pain levels when putting shoes or at rest 13% versus 4% ($p = 0.161$), when rising from a chair 16% versus 6% ($p = 0.123$), after the first steps 16% versus 8% ($p = 0.236$) or after a long walk 29% versus 19% ($p = 0.26$). In the MoP goup, patients with either revision, radiographic signs of osteolysis or radiolucent lines did not have significantly different functional scores compared to those without ($p = 0.302$-$0.978$).

The linear wear in the CoC group was below detection limit of the Imagika software. In contrast, in the MoP group, for the unrevised hips, total linear

wear averaged 2.3 mm (SD 1 mm, range 0.4 to 4.3 mm). At last FU, 10 MoP cases had more than 3.0 mm total linear wear ; they are being followed closely as they may need revision surgery. Annual wear averaged 0.19 mm/year (SD 0.08 mm/year, range 0.04 to 0.36 mm/year) with 29/47 of hips being above 0.2 mm/year. Both total wear and annual wear rates in the MoP group were significantly different from those in the CoC group ($p < 0.001$). We did not find significant correlations between annual PE wear and implantation length ($p = 0.64$), cup inclination ($p = 0.6$), femoral offset ($p = 0.88$), UCLA activity score ($p = 0.91$), PMA score ($p = 0.5$), and WOMAC scale ($p = 0.76$).

Local osteolysis zones were noted around components in 10/47 of MoP (5/39 MoP not revised and 5/8 MoP revised) versus 1/42 of CoC (including the sole revised case) ($p = 0.032$). In the MoP group, 1 stem not revised has cement fracture and stem subsidence and is considered loose secondary to osteolysis. All MoP patients with osteolysis had mean annual wear of more than 0.2 mm/year, meaning that 10/29 of hips with more than 0.2 mm/year wear developed osteolysis. Partial progressive radiolucent lines around components were observed in 10/47 of MoP 3/42 of CoC ($p = 0.075$). No ceramic fracture or squeaking occurred during the FU period.

## DISCUSSION

As THA is being offered to younger patients, we need to choose the best implants for optimal performance. With MoP bearings, osteolysis resulting from CPE wear debris is one of the most common causes of implant failure in this young population. Current new, alternative bearings are still under evaluation (*61*). Direct comparison of the performances of CoC and MoP bearings is needed to determine their real value in the long-term.

Our findings should be viewed in the light of our study limitations. First, we considered CPE as the control group. When this study was designed (1994-1995), CPE was the gold standard friction pairing. However, there is increasing evidence showing the clinical advantages of XLPE versus CPE (*28,47*). On the other hand, as reported in the 2010 Swedish Hip Register, 60% of PE used in Sweden are CPE and in 2011, Malchau *et al* raised concerns regarding the fast XLPE adoption with limited scientific data (*47*). More recently, Engh *et al* showed in a randomized study comparing XLPE and conventional PE at 10 years follow-up, a lower revision rate for wear related complication (0% vs 5.3%, $p = 0.003$) and reduced wear 0.04 versus 0.22 mm/y ($p < 0.001$) favouring the XLPE (*25*). Even if a similar study should be undertaken comparing XLPE as a control group, our study is the longest follow-up RCT comparing CoC to MoP bearing. As shown with this study, long enough follow-up is needed to truly determine the value of alternative bearings in THA. Secondly, Ceraver's PE sterilisation method changed over our study period. Ethylene oxide was used for the cases in the first 2 years and gamma irradiation in argon thereafter. Our study design did not allow us to compare performances of the two PE types. Third, metal backed PE components with PE thinner than 8 mm have been associated with increased wear rate (*23,37*). In the present study, Cerafit acetabular shells of 50 mm and 52 mm had 8.6 and 9.6 mm PE thickness (at 30° from their pole). In our study, 9 PE hips had shells of 50 mm and 6 of 52 mm and no statistical correlation was found between revision rate and shell size ($p = 0.22$), nor when shell size was divided in two groups : $\leq 52$ mm and $> 52$ mm ($p = 0.1$). Fourth, radiographic study with plain films underestimates the extent of osteolysis compared to computed tomography, which is more sensitive (*34*). Finally, 16 hips (11.4%) were lost to FU, 11 CoC and 5 MoP ($p = 0.125$). No significant difference in patient demographics was apparent between the lost-to-FU group and the group available at last FU.

At average FU of 12.3 years, a significant difference in the aseptic revision rate favoured the CoC group : 1/71 (1.4%) versus 8/69 (11.4%) in the MoP group ($p = 0.017$). In addition, 10 unrevised MoP hips had more than 3 mm PE linear wear, and 5 others had progressive local osteolysis with 1 loose femoral stem on radiography. All revisions in the MoP group were the consequence of wear-related complications, and the most significant factors correlated with revision risk were increased annual wear (0.3 mm/year in the revised group versus

0.2 mm/year for non-revised, p = 0.01) and higher acetabular component inclination (p = 0.024). In contrast, the sole revision in the CoC group was performed for a mechanically-loose femoral stem associated with an undersized cemented titanium stem.

In the literature, only 1 RCT (*16*) compared the same bearings – 144 CoC vs 72 MoP – with mean 10.3-year FU (10 to 12.4 years). Patient mean age was 53.7 years. The MoP group had higher osteolysis (26% vs 0%) and revision rates for any reason (10.5% vs 3.1%). Six patients were revised in the CoC group : 1 ceramic fracture at 9.2-year FU, 2 periprosthetic fractures, 2 infections, and 1 instability. Ten were revised in the MoP group : 3 severe osteolyses, 3 instabilities, 2 infections, 1 fracture, and 1 leg length discrepancy. Only 1 implant was loose (1 cup in MoP group) (*16*). Our results are comparable to those in other observational studies and registries (Tables II & III).

Table II. — Results from observational studies describing outcomes of MoP and CoC bearing surfaces at long-term FU in young patients

| | Bearing surface | FU (years) | Age of group (years) | Number of hips | Number of revisions | Osteolysis rate | Mean annual wear (mm/year) | Implant survival rate |
|---|---|---|---|---|---|---|---|---|
| Crowther and Lachiewicz (*14*) | MoP | 11 | Mean 37 years | 56 | 5 loosenings, 2 osteolyses, 1 infection, 1 pain | 23% pelvis osteolyses | 0.15 | NA |
| Emms *et al* (*24*) | MoP | 11.6 | Median 54 years | 280 | 62 hips (22.5%) mostly loosening, osteolysis, worn liner exchange | 17.1% of the remaining cup, 15% of the remaining stem | 0.25 in revised group | 91.2% at 10 years 56.3% at 14 years |
| Boyer *et al* (*5*) | CoC | 10 | < 50 years | 76 | 1 loosening, 1 ceramic fracture, 1 infection, 1 instability | None | Not studied | 92% at 10 years for any reason |
| Yeung *et al* (*72*) | CoC | 10.9 | Mean 58 years | 244 | 1 stem loosening, 1 infection, 4 fractures, 4 psoas tendinitis, 1 nerve palsy | None | Not studied | 99.6% at 10 years for aseptic loosening, 98% for any reason |

Table III. — Results from hip registers describing outcomes of MoP and CoC bearing surfaces

| | Bearing surface | Age of group (years) | Number of hips | Implant survival rate |
|---|---|---|---|---|
| 2007 Swedish Hip Register (*38*) | MoP | 50 to 59 years | NA | 90% at 10 years 78% at 16 years in men and 68% in women |
| Finnish Arthroplasty Registry (*46*) | MoP | 55 to 64 years | NA | 95% at 10 years 81% at 15 years |
| 2011 Australian National Joint Replacement Registry (*30*) | MoP | NA | 8,482 at 7 years 668 at 10 years | 95.2% at 7 years 92.9% at 10 years |
| | CoC | NA | 6,946 at 7 years 301 at 10 years | 95.8% at 7 years 94.6% at 10 years |

We were unable to measure any wear on the ceramic couple as its wear rate is below the detection limit of the Imagika software. Our PE linear wear rate of 0.19 mm/year is similar to wear rates reported by other authors in such young patients (0.141-0.246 mm/year) (*8,14,21,24,40*). Excessive acetabular component abduction is a well-recognized factor associated with increased PE wear (*1,22,59,71*) and should be avoided. In our study, revised hips had mean acetabular component abduction of 55.2°, which is above the recommended range of 35-45° (*35,52*). Surprisingly, we did not find positive correlations between annual wear rate and acetabular component abduction ($p = 0.6$). In contrast, in our short-term study (mean 6.5 years), increased cup inclination was highly correlated with increased annual wear rate ($p = 0.004$) (*67*). This difference could be partially explained by the 6 patients who underwent revision between both studies ; these patients had very high wear rates and high cup inclination. After their revision, they stopped contributing to the group data.

In our study, 10/47 of the MoP group incurred osteolysis, and the annual wear threshold of 0.2 mm/year seemed to be significant for osteolysis development ($p = 0.025$). We believe that such ostelolysis was secondary to granulomatous reaction to PE debris as consequence of the macrophagic activation (*1*). No osteolytic reactions were noted in our CoC group. Some observational studies have demonstrated a low osteolysis rate (*15,16,43*) and non-significant macrophage activation with CoC (*57*). *In vitro* investigations comparing macrophagic reaction to either alumina or CPE particle debris have shown that low alumina debris is needed to activate macrophages but macrophage apoptosis occurred sooner and more extensively than with PE debris, which may explain the lower inflammatory response to alumina particles and the lower incidence of osteolysis (*11,53*). Without being significant ($p = 0.075$), the radiolucent line rate was superior in the MoP group, 10/47 vs 3/42, and could be explained in the MoP group by an osteolytic reaction at the bone-cement interface.

With the small study group and number of implants used, no squeaking was reported spontaneously by patients, not even when specifically asked at last FU. Most studies have reported squeaking rates ranging from 0 to 2.5% (*16,60,63*). Cogan *et al*, implanting the same Ceraver devices as us, found 2.6% in 265 THA (*13*). Some studies have recorded squeaking rates as high as 20.9% (*33,36,55*) but implant malposition, implant designs and femoral stem types might have been responsible for such results (*39,69,70*).

The long-term results of this investigation demonstrate the advantages of CoC compared to metal on standard PE. A similar study should be undertaken to evaluate CoC benefits in comparison to metal on cross-linked PE in the young, active patients.

**Acknowledgments**

We thank Ceraver Osteal for their unrestricted research grant.

## REFERENCES

1. **Amstutz HC, Campbell P, Kossovsky N, Clarke IC.** Mechanism and clinical significance of wear debris-induced osteolysis. *Clin Orthop Relat Res* 1992 ; 276 : 7-18.
2. **Bellamy N.** Pain assessment in osteoarthritis : experience with the WOMAC osteoarthritis index. *Semin Arthritis Rheum* 1989 ; 18 (Suppl 2) : 14-17.
3. **Bohler M, Mochida Y, Bauer T W, Plenk H Jr, Salzer M.** Wear debris from two different alumina-on-alumina total hip arthroplasties. *J Bone Joint Surg 2000 ;* 82-B : 901-909.
4. **Boutin P.** [Alumina and its use in surgery of the hip. (Experimental study).] (in French). *Presse Med* 1971 ; 79 : 639-640.
5. **Boyer P, Huten D, Loriaut P *et al*.** 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 : 616-622.
6. **Bozic KJ, Kurtz S M, Lau E *et al.*** The epidemiology of revision total hip arthroplasty in the United States. *J Bone Joint Surg* 2009 ; 91-A : 128-133.
7. **Brooker AF, Bowerman JW, Robinson RA, Riley LH, Jr.** Ectopic ossification following total hip replacement. Incidence and a method of classification. *J Bone Joint Surg Am* 1973 ; 55 : 1629-1632.
8. **Capello W N, D'Antonio J A, Ramakrishnan R, Naughton M.** Continued improved wear with an annealed highly cross-linked polyethylene. *Clin Orthop Relat Res* 2011 ; 469 : 825-830.
9. **Catelas I, Huk OL, Petit A *et al.*** Flow cytometric analysis of macrophage response to ceramic and polyethylene

particles : effects of size, concentration, and composition. *J Biomed Mater Res* 1998 ; 41 : 600-607.

10. **Catelas I, Petit A, Marchand R *et al.*** Cytotoxicity and macrophage cytokine release induced by ceramic and polyethylene particles in vitro. *J Bone Joint Surg* 1999 ; 81-B) : 516-521.
11. **Catelas I, Petit A, Zukor DJ *et al.*** Induction of macrophage apoptosis by ceramic and polyethylene particles in vitro. *Biomaterials* 1999 ; 20 : 625-630.
12. **Caton J, Prudhon J L.** Over 25 years survival after Charnley's total hip arthroplasty. *Int Orthop* 2011 ; 35 : 185-188.
13. **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 : 206-210
14. **Crowther JD, Lachiewicz PF.** Survival and polyethylene wear of porous-coated acetabular components in patients less than fifty years old : results at nine to fourteen years. *J Bone Joint Surg* 2002 ; 84-A : 729-735.
15. **D'Antonio J, Capello W, Manley M, Naughton M, Sutton K.** Alumina ceramic bearings for total hip arthroplasty : five-year results of a prospective randomized study. *Clin Orthop Relat Res* 2005 ; 436 : 164-171.
16. **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.
17. **d'Aubigné RM, Postel M.** Functional results of hip arthroplasty with acrylic prosthesis. *J Bone Joint Surg* 1954 ; 36-A : 451-475.
18. **Dahl J, Soderlund P, Nivbrant B, Nordsletten L, Rohrl SM.** Less wear with aluminium-oxide heads than cobalt-chrome heads with ultra high molecular weight cemented polyethylene cups: a ten-year follow-up with radiostereometry. *Int Orthop* 2012 ; 36 : 485-490.
19. **Daras M, Macaulay W.** Total hip arthroplasty in young patients with osteoarthritis. *Am J Orthop (Belle Mead NJ)* 2009 ; 38 : 125-129.
20. **DeLee JG, Charnley J.** Radiological demarcation of cemented sockets in total hip replacement. *Clin Orthop Relat Res* 1976 ; 121 : 20-32.
21. **Devane PA, Robinson EJ, Bourne RB *et al.*** Measurement of polyethylene wear in acetabular components inserted with and without cement. A randomized trial. *J Bone Joint Surg Am* 1997 ; 79(5) : 682-689.
22. **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.
23. **Elfick AP, Hall RM, Pinder IM, Unsworth A.** Wear in retrieved acetabular components : effect of femoral head radius and patient parameters. *J Arthroplasty* 1998 ; 13 : 291-295.
24. **Emms NW, Stockley I, Hamer AJ, Wilkinson JM.** Long-term outcome of a cementless, hemispherical, press-fit acetabular component : survivorship analysis and dose-response relationship to linear polyethylene wear. *J Bone Joint Surg* 2010 ; 92-B : 856-861.
25. **Engh CA Jr, Hopper RH Jr, Huynh C *et al.*** A prospective, randomized study of cross-linked and non-cross-linked polyethylene for total hip arthroplasty at 10-year follow-up. *J Arthroplasty* 2012 ; 27(Suppl) : 2-7.
26. **Engh CA, Massin P, Suthers KE.** Roentgenographic assessment of the biologic fixation of porous-surfaced femoral components. *Clin Orthop Relat Res 1990* ; 257 : 107-128.
27. **Fritsch E W, Gleitz M.** Ceramic femoral head fractures in total hip arthroplasty. *Clin Orthop Relat Res* 1996 ; 328 : 129-136.
28. **Garellick GKJ, Herberts P.** Swedish Hip Arthroplasty Register. Annual Report 2010. Edited.
29. **Girard J, Touraine D, Soenen M *et al.*** [Measurement of head penetration on digitalized radiographs : reproducibility and accuracy.] (in French). *Rev Chir Orthop Reparatrice Appar Mot* 2005 ; 91 : 137-142.
30. **Graves SDD, De Steiger R.** AOA national joint replacement registry 2010. Annual report 2011. Edited.
31. **Griffith MJ, Seidenstein MK, Williams D, Charnley J.** Socket wear in Charnley low friction arthroplasty of the hip. *Clin Orthop Relat Res* 1978 ; 137 : 37-47.
32. **Gruen TA, McNeice GM, Amstutz HC.** "Modes of failure" of cemented stem-type femoral components : a radiographic analysis of loosening. *Clin Orthop Relat Res* 1979 ; 141 : 17-27.
33. **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 : 207-213.
34. **Hernigou P, Zilber S, Filippini P, Poignard A.** Ceramic-ceramic bearing decreases osteolysis : a 20-year study versus ceramic-polyethylene on the contralateral hip. *Clin Orthop Relat Res* 2009 ; 467 : 2274-2280.
35. **Hirakawa K, Mitsugi N, Koshino T *et al.*** Effect of acetabular cup position and orientation in cemented total hip arthroplasty. *Clin Orthop Relat Res* 2001 ; 388 : 135-142.
36. **Jarrett CA, Ranawat AS, Bruzzone M *et al.*** The squeaking hip : a phenomenon of ceramic-on-ceramic total hip arthroplasty. *J Bone Joint Surg* 2009 ; 91-A : 1344-1349.
37. **Kabo JM, Gebhard JS, Loren G, Amstutz HC.** In vivo wear of polyethylene acetabular components. *J Bone Joint Surg* 1993 ; 75-B : 254-258.
38. **Kärrholm JGG, Herberts P.** Swedish Hip Register Annual Report 2007. Edited.
39. **Keurentjes JC, Kuipers RM, Wever DJ, Schreurs BW.** High incidence of squeaking in THAs with alumina ceramic-on-ceramic bearings. *Clin Orthop Relat Res* 2008 ; 466 : 1438-1443.
40. **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 : 2262-2277.

41. **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* 2010 ; 92-A : 1715-1719.
42. **Lerouge S, Huk O, Yahia L, Witvoet J, Sedel L.** Ceramic-ceramic and metal-polyethylene total hip replacements : comparison of pseudomembranes after loosening. *J Bone Joint Surg* 1997 ; 79-B : 135-139.
43. **Lewis PM, Al-Belooshi A, Olsen M, Schemitch EH, Waddell JP.** Prospective randomized trial comparing alumina ceramic-on-ceramic with ceramic-on-conventional polyethylene bearings in total hip arthroplasty. *J Arthroplasty* 2010 ; 25 : 392-397.
44. **Lusty P J, Watson A, Tuke M A *et al.*** Wear and acetabular component orientation in third generation alumina-on-alumina ceramic bearings : an analysis of 33 retrievals [corrected]. *J Bone Joint Surg* 2007 ; 89-B : 1158-1164.
45. **Makela K T, Eskelinen A, Pulkkinen P, Paavolainen P, Remes V.** Results of 3,668 primary total hip replacements for primary osteoarthritis in patients under the age of 55 years. *Acta Orthop* 2011 ; 82 : 521-529.
46. **Makela KT, Eskelinen A, Pulkkinen P, Paavolainen P, Remes V.** Total hip arthroplasty for primary osteoarthritis in patients fifty-five years of age or older. An analysis of the Finnish arthroplasty registry. *J Bone Joint Surg* 2008 ; 90-A : 2160-2170.
47. **Malchau H, Bragdon CR, Muratoglu OK.** The stepwise introduction of innovation into orthopedic surgery : the next level of dilemmas. *J Arthroplasty* 2011 ; 26 : 825-831.
48. **Massin P, Schmidt L, Engh CA.** Evaluation of cementless acetabular component migration. An experimental study. *J Arthroplasty* 1989 ; 4 : 245-251.
49. **McGrory BJ, Morrey BF, Cahalan TD, An KN, Cabanela ME.** Effect of femoral offset on range of motion and abductor muscle strength after total hip arthroplasty. *J Bone Joint Surg* 1995 ; 77-B : 865-869.
50. **Montesi M, Beraudi A, Stea S *et al.*** Monocyte Chemoattractant Protein 1 expression in synovial fluid of patients with total hip arthroplasty. *Artif Organs* 2011 ; 36 : 487-491.
51. **Mulroy RD Jr, Harris WH.** The effect of improved cementing techniques on component loosening in total hip replacement. An 11-year radiographic review. *J Bone Joint Surg* 1990 ; 72-B : 757-760.
52. **Patil S, Bergula A, Chen PC, Colwell CW Jr, D'Lima DD.** Polyethylene wear and acetabular component orientation. *J Bone Joint Surg* 2003 ; 85-A Suppl 4 : 56-63.
53. **Petit A, Catelas I, Antoniou J, Zukor DJ, Huk OL.** Differential apoptotic response of J774 macrophages to alumina and ultra-high-molecular-weight polyethylene particles. *J Orthop Res* 2002 ; 20 : 9-15.
54. **Petsatodis 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* 2010 ; 92-A : 639-644.
55. **Restrepo C, Matar WY, Parvizi J, Rothman RH, Hozack WJ.** Natural history of squeaking after total hip arthroplasty. *Clin Orthop Relat Res* 2010 ; 468 : 2340-2345.
56. **Santavirta S, Konttinen YT, Bergroth V *et al.*** Aggressive granulomatous lesions associated with hip arthroplasty. Immunopathological studies. *J Bone Joint Surg* 1990 ; 72-A : 252-258.
57. **Savarino L, Baldini N, Ciapetti G, Pellacani A, Giunti A.** Is wear debris responsible for failure in alumina-on-alumina implants ? *Acta Orthop* 2009 ; 80 : 162-167.
58. **Schmalzried TP, Jasty M, Harris WH.** Periprosthetic bone loss in total hip arthroplasty. Polyethylene wear debris and the concept of the effective joint space. *J Bone Joint Surg* 1992 ; 74-A : 849-863.
59. **Sethi RK, Neavyn MJ, Rubash HE, Shanbhag AS.** Macrophage response to cross-linked and conventional UHMWPE. *Biomaterials* 2003 ; 24 : 2561-2573.
60. **Sexton SA, Yeung E, Jackson MP *et al.*** The role of patient factors and implant position in squeaking of ceramic-on-ceramic total hip replacements. *J Bone Joint Surg* 2011 ; 93-B : 439-442.
61. **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 : 1281-1287.
62. **Springer BD, Connelly SE, Odum SM *et al.*** Cementless femoral components in young patients : review and meta-analysis of total hip arthroplasty and hip resurfacing. *J Arthroplasty* 2009 ; 24 (6 Suppl) : 2-8.
63. **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* 2011 ; 93-B : 1017-1020.
64. **Sychterz CJ, Young AM, Engh CA.** Effect of radiographic quality on computer-assisted head penetration measurements. *Clin Orthop Relat Res* 2001 ; 386 : 150-158.
65. **Tipper JL, Hatton A, Nevelos JE *et al.*** Alumina-alumina artificial hip joints. Part II : characterisation of the wear debris from in vitro hip joint simulations. *Biomaterials* 2002 ; 23 : 3441-3448.
66. **Veigl D, Vavrik P, Pokorny D *et al.*** [Comparison of in vivo characteristics of polyethylene wear particles produced by a metal and a ceramic femoral component in total knee replacement]. *Acta Chir Orthop Traumatol Cech* 2011 ; 78 : 49-55.
67. **Vendittoli P, Girard J, Lavigne M, Lavoie P, Duval N.** Comparison of alumina-alumina to metal-polyethylene bearing surfaces in THA : a randomized study with 4- to 9-years follow-up. *Acta Orthop Belg* 2007 ; 73 : 468-477.
68. **Von Schewelov T, Sanzen L, Borlin N, Markusson P, Onsten I.** Accuracy of radiographic and radiostereometric

wear measurement of different hip prostheses : an experimental study. *Acta Orthop Scand* 2004 ; 75 : 691-700.

**69. Walter WL, Kurtz SM, Esposito C *et al.*** Retrieval analysis of squeaking alumina ceramic-on-ceramic bearings. *J Bone Joint Surg* 2011 ; 93-B : 1597-1601.

**70. Walter WL, O'Toole GC, Walter WK, Ellis A, Zicat BA.** Squeaking in ceramic-on-ceramic hips : the importance of acetabular component orientation. *J Arthroplasty* 2007 ; 22 : 496-503.

**71. Wilkinson JM, Hamer AJ, Stockley I, Eastell R.** Polyethylene wear rate and osteolysis : critical threshold versus continuous dose-response relationship. *J Orthop Res* 2005 ; 23 : 520-525.

**72. Yeung E, Bott PT, Chana R *et al.*** Mid-term results of third-generation alumina-on-alumina ceramic bearings in cementless total hip arthroplasty : a ten-year minimum follow-up. *J Bone Joint Surg* 2012 ; 94-A : 138-144.

**73. Zywiel 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 : 1536-1546.