

Lessons learnt from early failure of a patient trial with a polymer-on-polymer resurfacing hip arthroplasty

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Background and purpose — Hip resurfacing (HR) is a treatment option promoted for hip arthritis in young and active patients. However, adverse reactions to metal are a concern and the search for non-metallic bearing options proceeds. We present the first clinical study performed in patients using a newly developed hydrophilic polymer-on-polymer hip resurfacing device.

Patients and methods — After performing extensive hip simulator tests, biocompatibility testing and animal tests (ISO 14242-1,3; 10993-3,4,5,10,11), approval was obtained from the IRB committee to enroll 15 patients in the first clinical study in humans using this experimental polymer-on-polymer hip resurfacing device. All surgeries were done by 2 experienced hip resurfacing surgeons. Clinical scores and standard radiographs as well as routine MRIs were obtained at regular intervals.

Results — The surgical technique proved feasible with successful implantation of the new device using PMMA cement fixation on both sides without complications. Postoperative imaging revealed a well-positioned and well-fixed polymer resurfacing hip arthroplasty in all 4 initial cases. All 4 patients were free of pain and had good function for the first 2 months. However, in all 4 cases early cup loosening occurred between 8 and 11 weeks after surgery, necessitating immediate closure of the study. All 4 patients had a reoperation and were revised to a conventional THA. Retrieval analyses confirmed early cup loosening at the implant–cement interface in all 4 cases. The femoral components remained well attached to the cement. The periprosthetic tissues showed only small amounts of polymeric wear debris and there was only a very mild inflammatory reaction to this.

Interpretation — Early cup loosening mandated a premature arrest of this study. After additional laboratory testing this failure mode was found to be the result of a small, yet measurable contraction in the cup size after exposing these implants to biological

fluid divalent ion fluctuations *in vivo*. Currently used preclinical tests had failed to detect this failure mechanism. Modification of the polymer is essential to overcome these problems and before the potential of a polymer-on-polymer resurfacing arthroplasty may be further evaluated in patients. ■

Resurfacing hip arthroplasty remains an interesting treatment option for hip arthritis in young and active patients. Femoral bone preservation facilitating future revisions, a high level of activity after surgery and a low incidence of postoperative dislocations are proven advantages (Bisseling et al. 2015a, Haddad et al. 2015, Van Der Straeten et al. 2016). However, the use and acceptance of hip resurfacing has dropped dramatically following encountered adverse reactions to metal debris around metal-on-metal bearing implants (Dunbar et al. 2014, Bisseling et al. 2015b, Liow et al. 2016, Matharu et al. 2016). Since the resurfacing concept itself has proven to provide advantages, a search for alternative bearing options and materials proceeds.

One option may be using polymers in combination with hip resurfacing designs. However, so far, only limited data on the clinical use of polycarbonate-urethane (PCU) polymers as an innovative bearing are available in the literature although these materials have attracted interest for many years (Bergmann et al. 2001, Kurtz 2008, Jones et al. 2009, St John and Gupta 2012, St John 2014). In laboratory hip simulator testing, the material loss measured from novel PCU cups was 24% lower than for cross-linked ultra-high-molecular-weight polyethylene (UHMWPE) cups (St John and Gupta 2012). Preliminary data from the clinical studies available focus on the use of a



Figure 1. The Gradion Hip TCR implant (Biomimmedica, Inc., USA).

total hip arthroplasty (THA) using a PCU acetabular component (TriboFit System; Stryker, Kalamazoo, MI, USA) coupled with a large-diameter metal femoral head (Moroni et al. 2012, Siebert et al. 2009, Cadossi et al. 2013). Results were promising in the first 2 studies (Moroni et al. 2012, Siebert et al. 2009) whereas further use of this cup for treatment of femoral neck fractures in the elderly was not recommended because of a high early acetabular revision rate of the polymer implants (Cadossi et al. 2013). However, both in-vitro and preliminary clinical studies support the idea that polymers, such as PCU, may be an interesting non-metallic bearing option and warrant further evaluation.

In contrast to the earlier reported TriboFit System using PCU liners bearing against metallic femoral heads, the Gradion Hip Total Cartilage Replacement (TCR) System (Biomimmedica, Inc., San Francisco, CA, USA) used in this study is an innovative polymer-on-polymer THA device, where both femoral and acetabular components are composed of a hydrated polymeric material that has similar structure, geometry, and functional properties to cartilage (Figure 1). Each component consists of 2 polymers, water, and small amounts of physiologic salts. For the 2 polymers, thermoplastic polyether urethane and polyelectrolyte, the weight ratio varies through the thickness of the device, with the highest percentage of the hydrophilic polyelectrolyte at the bearing surface and polyether urethane at the anchoring surface.

Prior to the current clinical study, the Gradion Hip TCR implant had already been tested elsewhere for up to 10 million cycles in a separate hip simulator study under standard gait loading with an overall wear rate of 0.26 ± 0.20 mg/Mc (unpublished data). In that study, the number of particles produced per million cycles appeared to be approximately 1,000 times lower than for metal-on-crosslinked polyethylene THA and the mean particle size (0.10 – 0.25 μm) was around the lower range for proinflammatory particle size (0.3 – 10 μm) (Green et al. 1998). In addition, a company report was available where bio-responsiveness to the Gradion implant was also approved in a limited hemi-arthroplasty study in goats.

Subsequent to these earlier studies elsewhere, a human cadaveric study of the cement fixation of the Gradion Hip TCR implants was repeated at our institution. Dissected pelvic and femoral bone tissues with the Gradion Hip TCR implants were embedded in acrylic bone cement—Autoplast (Condu-lur, Switzerland). For the test, the specimens were positioned in a water bath on the table of the tensile testing machine (MTS Corp, Eden Prairie, MN, USA). Each specimen was subjected to cyclic loading representing normal gait (pelvis orientation: 7° in the sagittal plane, 8° in the coronal plane, and 49° in the transverse plane) and stair climbing (pelvis orientation: 13° in the sagittal plane, 5° in the coronal plane, and 20° in the transverse plane) (Bergmann et al. 2001). Normal walking load (100 N to 1,870 N) and stair-climbing load (100 N to 1,970 N) were applied at frequency of 2 Hz for 72,000 cycles each. Device–cement bond analysis was performed by thumb pressure on the rims of the acetabular and femoral device in 3–4 locations and by applying a small amount of black dye (Rotring, Germany) with a syringe to the device–cement interface at the rim of the acetabular and femoral devices. Photographs of the rim of the device were taken after 72,000 cycles and dark areas subsequently indicated where detachment had occurred. In addition, device–cement–bone analysis via sectioning was performed using UV light to check if there were any cement cracks, which absorbed fluorescent dye during loading. These test results confirmed proper strength of the cement fixation for the implants on both sides (unpublished data).

After Gradion Hip TCR passed both the available preclinical tests performed elsewhere and the mechanical test repeated at our institution, the authors and the company agreed to proceed with a clinical investigation. We present now the first results from a safety and performance study in patients with this new polymer-on-polymer hip resurfacing device.

Patients and methods

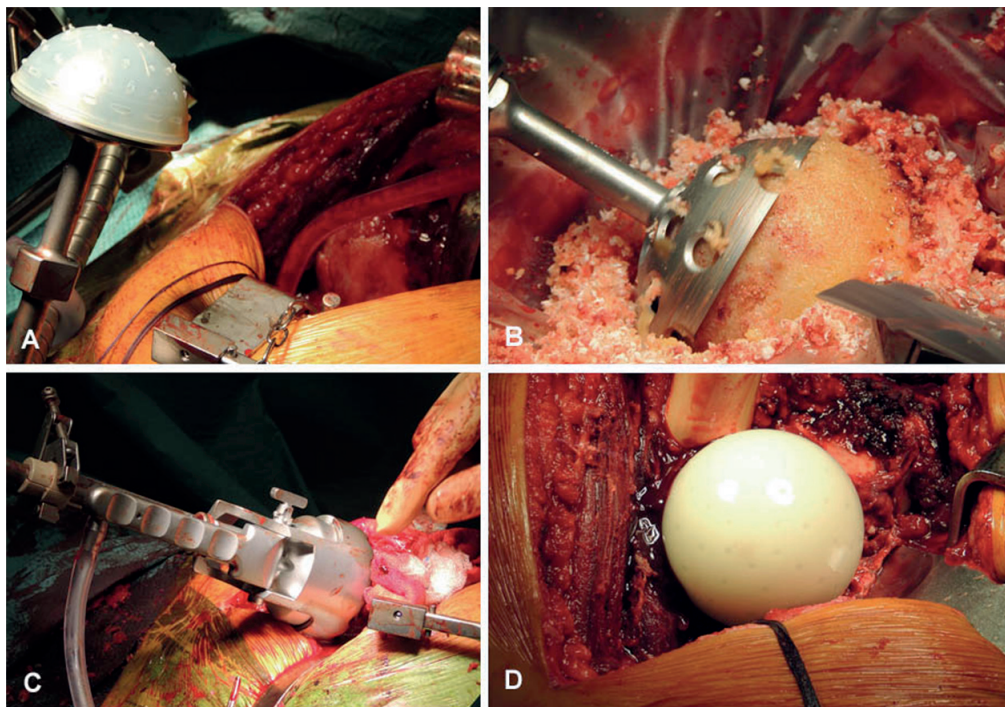
Inclusion criteria were patients aged > 18 years and severe osteoarthritis of the hip with normal anatomy of the joint. Patients with a potential allergy to polyether urethane, sodium polyacrylate, bone cement, or any of its components were excluded by means of a preoperative questionnaire.

Surgical technique (Figure 2)

All surgeries were performed in collaboration by 2 out of 3 experienced hip (resurfacing) surgeons (JvS, BWS, PB) using a posterolateral approach. The surgical technique was matched with a hip resurfacing procedure as has been described before (Amstutz et al. 2006, Smolders et al. 2011). The Gradion HIP TCR was implanted and both the acetabular and the femoral component were cemented with low-viscosity cement after standard reaming. Both the acetabular and the femoral side were slightly over-reamed (1 mm) to

Figure 2.

- A. Intraoperative view of the acetabular component which is positioned on a vacuum suction device facilitating cemented implantation of the flexible device in a perfect concave shape. Cement spacers are present to facilitate cementing.
- B. Preparation of the femoral head by reaming.
- C. Subsequently the flexible femoral component is cemented on the femoral head and again a vacuum suction device is used to facilitate curing of the cement with the desired convex shape.
- D. The femoral component after cementing. Adequate cementing technique can be confirmed through the transparency of the component.



allow adequate cementing and avoid any potential for deformation during insertion. Prior to cementing, the acetabular component was fitted on a vacuum suction device facilitating cemented implantation of the flexible device in a perfect concave shape. Accordingly, preparation of the femoral head was performed by reaming, after which the flexible femoral component was cemented onto the femoral head again using a vacuum suction device to facilitate curing of the cement with the desired convex shape. The use of these custom-made vacuum suction devices while cementing ensured maintenance of a perfectly matched concave and convex spherical shape for the acetabular and femoral components, as had been confirmed earlier during in-vitro testing of the cementing technique on saw bones. Patients received antibiotic prophylaxis with cephalosporin preoperatively and 24 h postoperatively, periarticular ossification prophylaxis using diclofenac 50 mg for 3 days, and thrombosis prophylaxis with nadroparine (2,850 IE subcutaneous) during hospital admission and continued for 6 weeks after surgery.

Clinical and radiographic evaluation

Clinical scores, including the Harris Hip Score (HHS), the University of California at Los Angeles (UCLA) activity score, SF-12, Oxford hip score (OHS), and VAS implant satisfaction, were assessed by an independent research assistant preoperatively and planned at 3, 6, 12, and 24 months. Conventional pelvic radiographs were obtained at the same time points. In addition, given the non-metallic nature of the device, an MRI scan of the operated hip was planned for the first week after surgery and after 3 and 12 months.

Retrieval analysis evaluation

4 femoral heads and 3 acetabular components were submitted for retrieval analysis. Revision specimens were not immersed in formalin or any other fluid, but were preserved in sealed plastic jars moistened with physiological saline for transport to the retrieval lab. In 2 cases, periprosthetic tissues were collected and were fixed in formalin and processed routinely for standard HE paraffin sections. The femoral and acetabular components were visually inspected using a hand lens and a stereo microscope. Although the femoral heads were intact and not implicated in the cause for revision, they were sectioned to allow inspection of the cement interface. This was done using a 4 mm-thick coronal section cut from the approximate middle of each femoral head. The sectioned pieces were photographed and radiographed. Following these procedures, the polymeric layer of the sectioned Gradion implant was manually removed. The bone sections were fixed in formalin and then decalcified to facilitate histological processing into a paraffin block and the production of HE-stained histological sections. These bone sections and the periprosthetic tissue sections were reviewed by light microscopy.

Ethics, funding, and potential conflicts of interest

Institutional Review Board (IRB) approval (NL45059.091.13 / reg. nr. 2013/282; date of issue August 15, 2013) was obtained for the enrollment of 15 patients in which a cemented Gradion Hip TCR device was to be implanted for treatment of hip osteoarthritis. To each patient the background of the innovative device and experimental character of the procedure were explained in detail by means of 6-page study information.

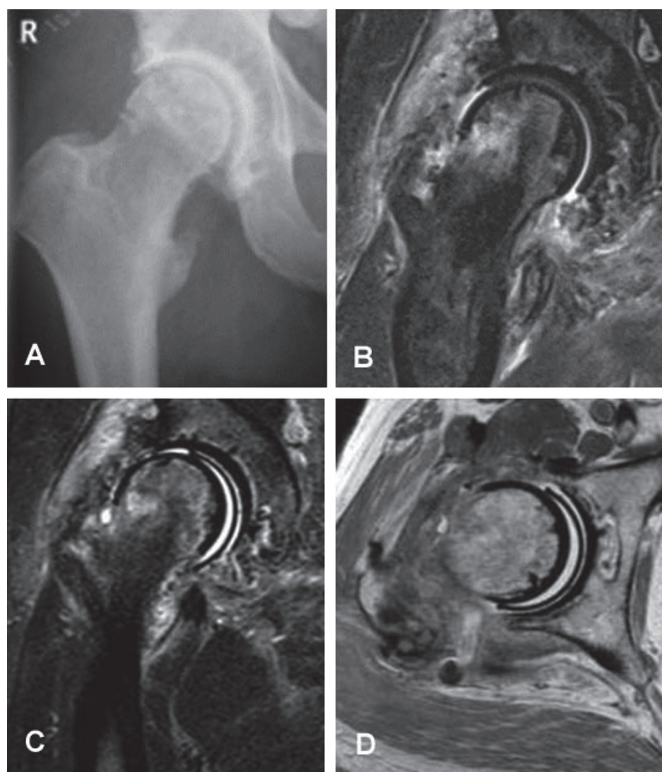


Figure 3.

- A. Postoperative radiographs with the radiolucent resurfacing device in situ. Both the acetabular and the femoral component are cemented.
 B. T2 weighted MRI scan of the hip one day after implantation of the new device. From its non-metallic nature both well-fixed and well-positioned components are clearly visible both on the acetabular and on the femoral side.
 C. Coronal view on the T2 weighted MRI 8 weeks after implantation. The femoral component remained well fixed; however, the acetabular component has come loose from its cement mantle and has rotated dorsal-caudally.
 D. Transverse MRI view showing the loosening.

Subsequently, all patients signed informed consent. Institutional financial support was provided by Biomimedica Inc. There was no personal conflict of interest.

Results

The surgical technique was feasible with successful implantation of the new device. There were no perioperative complications with uneventful recovery and discharge 3 days after surgery in all 4 patients.

Postoperative radiographs and MRI revealed well-positioned and well-fixed components in all cases (Figure 3). As expected, the implant was clearly visible on MRI and the cement fixation in the subchondral bone appeared to cover the entire surface of both the acetabular and the femoral component. Also, both components had maintained their spherical contour fitting on MRI.

In the first weeks after surgery the patients performed well and were satisfied with their operation. 8 weeks after the first operation when 4 patients had been operated, the first patient reported recurrence of pain in the groin and limping. A new MRI revealed early loosening of the acetabular component. On both coronal and transverse slices the acetabular component was visible as it had come loose from its seemingly intact acetabular cement mantle (Figure 3). The acetabular component appeared to have decreased somewhat in diameter and as such had detached itself from the cement mantle. The femoral component, on the contrary, was still adequately fixed with a seemingly intact implant–PMMA and PMMA–bone interface. This serious adverse event was immediately reported to the IRB and further enrollment of patients was halted. All 4 patients had a similar early failure mechanism in the same period (8–11 weeks) with acetabular component loosening.

All 4 patients were revised and at surgery the acetabular implants were loose; the femoral implants appeared to be well fixed. Some macroscopic damage to the loose acetabular component seemed to have occurred as the loose component had been squeezed as a loose body between the intact femoral component and the acetabular cement mantle. The femoral head with attached femoral component, along with the loose cup, were sent for retrieval analysis. All hips were revised to a conventional total hip arthroplasty with good clinical results at their latest 2-year follow-up. In 1 patient an early deep infection occurred, which was treated successfully with debridement and antibiotics.

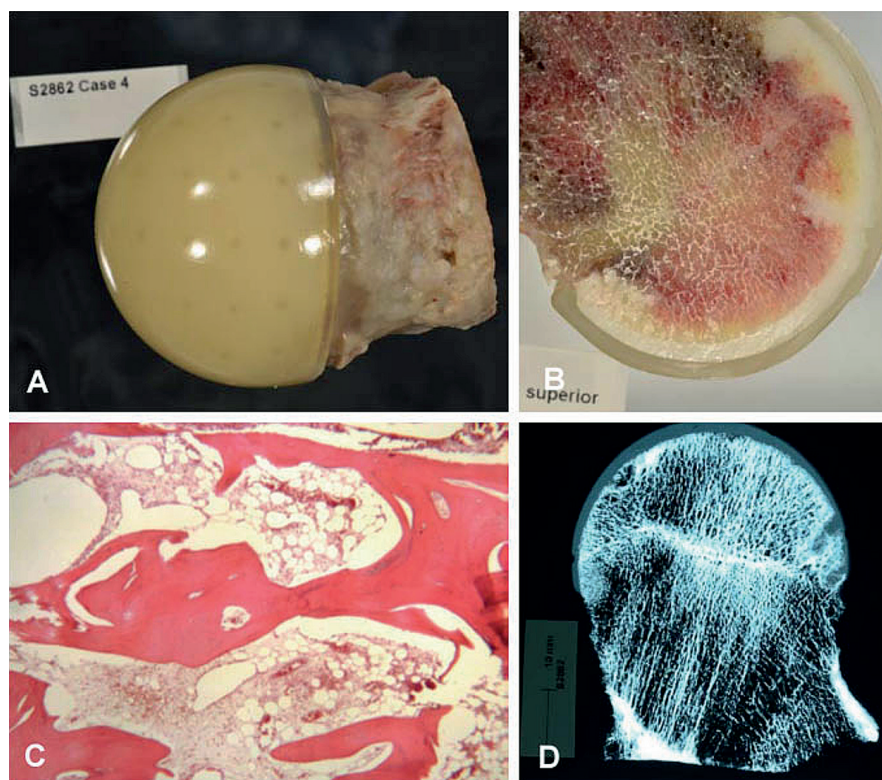
Retrieval analysis results (Figure 4)

In each case, the acetabular components showed variable amounts of gross damage. This took the form of distortion, abrasion, pitting, discoloration tears, or cracks. This damage appeared to have been the result of moving as a corpus liberum through the hip joint for a period of time between loosening and the revision procedure. The cement spacers on the back of the cups were irregularly textured, reduced in size and in many cases appeared to be abraded or cracked. The bearing surfaces typically showed fine to moderate scratches and occasional small pits or indents. In each of the 4 femoral heads, there was an intact femoral neck and the polymeric device was apparently well fixed to the bone. The bearing surfaces showed removal damage as well as focal, dull areas of moderately deep or light scratches and small pits, also possibly from compressive forces against the loose acetabular component.

The sections revealed variable degrees of cement penetration ranging from several millimeters to poor interdigitation of the cement with clear gaps. The middle sections of 2 of the femoral heads showed the presence of an interfacial fibrous membrane that was verified histologically. This membrane ranged from approximately 130 microns to nearly 0.8 mm thick and was present along nearly all of the convex inter-

Figure 4.

- A. Specimen of a femoral head with component. The intact femoral component was well fixed to the femur and besides some light scratches on the dome there were no signs of gross wear.
- B. Image following mid-cut sectioning. There is an intact and adequately thick cement mantle visible with keyholes. The bone/cement interface revealed good cement interdigitation and otherwise adequate fixation of the femoral component.
- C. Histology from the bone–cement interface (HE $\times 40$). Bone in the proximal superior interface shows some necrotic core bone as well as evidence of remodeling. The vessels within the fibrotic marrow indicate viability.
- D. Corresponding (B) microradiograph showing intact bone and interdigitation between the cement and the bone.



face. By contrast the sections from the other 2 femoral heads showed only thin (approx. 100–150 microns thick) intervening fibrous tissue, in less than 10% of the interface.

Microscopic examination of the bone throughout the middle sections of the 4 femoral heads showed that there was necrosis of the bone only at the interface that had been in direct contact with the interdigitating cement. Moderate necrosis (from 40% to 60%) of the bone within 2–3 mm of the interface was noted in 2 cases. In the 2 other femoral heads in which an intervening fibrous membrane had formed, necrosis of the interfacial bone was minimal, less than 10%. All of the other remaining bone in all 4 heads appeared viable.

The soft tissues from 2 cases were viable and vascular and consisted of mostly fibrous capsule-like tissue containing small numbers of macrophages and giant cells. A small amount of particulate bone cement, hematin pigment and opaque partly polarizable material was observed. In 1 case, the synovial lining was well preserved while areas of the second cases showed replacement of the synovial edge by fibrin. The tissue features were consistent with postoperative healing and repair. The ALVAL scores ranged from 1 + 1 + 1 to 3 + 1 + 1 (Campbell et al. 2010).

Discussion

This first clinical study implanting a fully polymeric hip resurfacing was prematurely terminated due to the unexpected

loosening of the acetabular components at the implant–cement interface in all 4 patients between 8 and 11 weeks.

Rigorous preclinical evaluation with wear testing, an animal experiment, hip simulator, and mechanical testing failed to predict this early failure mode. The femoral components seemed to perform adequately without loosening or fracture. We believe the observed light scratches and small pits on both bearing surfaces at time of retrieval analysis could be explained by the wear and tear from the acetabular component acting as a loose body against the femoral surface. We suppose contraction of the polymer when exposed to biological ion fluctuations caused this early mode of failure. This was confirmed by a simple in-vitro experiment now performed by the manufacturer where cemented acetabular components came loose from a saw-bone pelvis when exposed to a saline solution with an increasing concentration of free calcium ions. The fixation strength of the implant–cement interface proved insufficient to withstand these contractile forces on the acetabular side. This mode of failure was missed during cadaveric clinical testing at our institution since specimens were tested in a saline solution only without the addition of other ions present in vivo. As for the goat experiment performed elsewhere we believe the minimal acetabular contraction was also missed as only a femoral hemiprosthesis was tested.

In retrospect, one may conclude that both the acetabular and the femoral component should have been tested in an animal model; however, it is well recognized that there are no perfect animal models available to adequately test in-vivo perfor-

mance of all innovative joint arthroplasties. Had an acetabular component also been used in the goat study we believe the implant would have been so small that in terms of percentage the shrinkage may still have been too small to induce the early cup loosening we observed in the patient.

Based on previous studies (Siebert et al. 2009, Moroni et al. 2012, St John and Gupta 2012, Cadossi et al. 2013) polymers such as polycarbonate-urethane (PCU) are suggested as potential alternative bearings in future implants. Similar polymers were used in the Gradion device and, as such, this study is the first attempt to introduce a true polymer-on-polymer device. In spite of the dramatic early failure mechanism of the implant used in this study, we feel many lessons were learnt and warrant this publication.

Innovations may introduce new failure mechanisms that can be missed with currently accepted preclinical ISO-testing procedures. In retrospect, as clinicians we had been reassured too much by these tests and lack an adequate background on polymer biochemistry. Clearly, polymers have important behavioral characteristics that deviate from currently used non-flexible hard implant materials that have been rather inert and resistant to effects from the biological fluids around them. Clinicians and manufacturer's biochemistry experts have a completely different background, which can lead to a risk of overlooking consequences when bringing both worlds together in the introduction of innovations. In this study, for example, the rather simple potential for contraction in size of the polymer as a result of the presence of biological fluids was completely missed during preclinical testing by both.

This shrinkage problem may not be solely applicable to the Gradion device, and may be a more generalizable phenomenon for other polymers. But to our knowledge there are no references to this phenomenon in the literature. So far only a limited number of clinical studies on the use of polymers as an alternative bearing have been reported. Cadossi et al. (2013) compared a novel total hip arthroplasty comprising a polycarbonate-urethane (PCU) acetabular component (TriboFit System; Stryker) coupled with a large-diameter metal femoral head with the use of a conventional bipolar hemiarthroplasty in a randomized controlled trial for the treatment of displaced fractures of the femoral neck in elderly patients. The authors recommended against further use of the PCU acetabular component from relatively high early revision rates. In that study, contraction in size of the PCU acetabular component may also have played a role although this failure mechanism was not described in their paper.

Finally, the rather dramatic early failure mechanism in our trial may obscure the positive findings for potential use of these materials in the future. From the preclinical work done the material itself appears to have beneficial characteristics, namely that it is wear resistant, hydrophilic, non-metallic, and biocompatible. It is a major limitation of this clinical trial that the preclinical was not published.

In summary, polymers behave entirely different from conventional implant materials and as such introduce new failure mechanisms that can be overlooked using current preclinical testing protocols. Stepwise introduction of these innovations in clinical practice must be done with extreme care. Before clinical trials using polycarbonate-urethane (PCU) polymers as an alternative bearing can be initiated again we feel more research is mandatory to better understand the interaction of these materials with a biological environment. In addition, such preclinical work should be published.

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- Amstutz H C, Beaulé P E, Dorey F J, Le Duff M J, Campbell P A, Gruen T A. Metal-on-metal hybrid surface arthroplasty. Surgical technique. *J Bone Joint Surg Am* 2006; 88 (Suppl 1 Pt 2): 234-49.
- Bergmann G, Deuretzbacher G, Heller M, Graichen F, Rohlmann A, Strauss J, Duda G N. Hip contact forces and gait patterns from routine activities. *J Biomech* 2001; 34: 859-71.
- Bisseling P, Smolders J M H, Hol A, van Susante J L C. Metal ion levels and functional results following resurfacing hip arthroplasty versus conventional small-diameter metal-on-metal total hip arthroplasty: A 3 to 5 year follow-up of a randomized controlled trial. *J Arthroplasty* 2015a; 30 (1): 61-7.
- Bisseling P, de Wit B W K, Hol A M, van Gorp M J, van Kampen A, van Susante J L C. Similar incidence of periprosthetic fluid collections after ceramic-on-polyethylene total hip arthroplasties and metal-on-metal resurfacing arthroplasties. *Bone Joint J* 2015b; 97-B: 1175-82.
- Cadossi M, Chiarello E, Savarino L, Tedesco G, Baldini N, Faldini C, Giannini S. A comparison of hemiarthroplasty with a novel polycarbonate-urethane acetabular component for displaced intracapsular fractures of the femoral neck. *Bone Joint J* 2013; 95-B: 609-15.
- Campbell P, Ebrahimzadeh E, Nelson S, Takamura K, De Smet K, Amstutz H C. Histological features of pseudotumor-like tissues from metal-on-metal hips. *Clin Orthop Relat Res* 2010; 468 (9): 2321-7.
- Dunbar M J, Prasad V, Weerts B, Richardson G. Metal-on-metal hip surface replacement: The routine use is not justified. *Bone Joint J* 2014; 96-B (11 Suppl A): 17-21.
- Green T R, Fisher J, Stone M, Wroblewski B M, Ingham E. Polyethylene particles of a "critical size" are necessary for the induction of cytokines by macrophages in vitro. *Biomaterials* 1998; 19 (24): 2297-302.
- Haddad F S, Konan S, Tahmassebi J. A prospective comparative study of cementless total hip arthroplasty and hip resurfacing in patients under the age of 55 years: A ten-year follow-up. *Bone Joint J* 2015; 97-B (5): 617-22.
- Jones E, Scholes S C, Burgess I C, Ash H E, Unsworth A. Compliant layer bearings in artificial joints, Part 2: Simulator and fatigue testing to assess the durability of the interface between an elastomeric layer and a rigid substrate. *Proc Inst Mech Eng* 2009; 223 (1): 1-12.
- Kurtz S M. Retrieval analysis of a polycarbonate-urethane acetabular cup: A case report. *J Long Term Eff Med Implants* 2008; 18 (1): 69-74.
- Liow M H, Dimitriou D, Tsai T Y, Kwon Y M. Preoperative risk factors associated with poor outcomes of revision surgery for "pseudotumors" in patients with metal-on-metal hip arthroplasty. *J Arthroplasty* 2016; 31 (12): 2835-42.
- Matharu G S, Judge A, Murray D W, Pandit H G. Prevalence of and risk factors for hip resurfacing revision: a cohort study into the second decade after the operation. *J Bone Joint Surg Am* 2016; 98 (17): 1444-52.
- Moroni A, Nocco E, Hoque M, Diremiglio E, Buffoli D, Cantù F, Catalani S, Apostoli P. Cushion bearings versus large diameter head metal-on-metal. *Arch Orthop Trauma Surg* 2012; 132 (1): 123-9.

- Siebert W, Mai S, Moroni A, Chiarello E, Giannini S. A Two-year prospective and retrospective multi-center study of the TriboFit® Hip System. *J Long-Term Effects Medical Implants* 2009; 19 (2): 149-55.
- Smolders J M, Hol A, Rijnberg W J, van Susante J L C. Metal ion levels and functional results after either resurfacing hip arthroplasty or conventional metal-on-metal hip arthroplasty. *Acta Orthop* 2011; 82(5): 559-66.
- St John K R. The use of compliant layer prosthetic components in orthopedic joint repair and replacement: A review. *J Biomedical Materials Research Part B: Applied Biomaterials* 2014; 102 (6): 1332-41.
- St John K R, Gupta M. Evaluation of the wear performance of a polycarbonate-urethane acetabular component in a hip joint simulator and comparison with UHMWPE and cross-linked UHMWPE. *J Biomater Appl* 2012; 27 (1): 55-65.
- Van Der Straeten C, De Smet K A. Current expert views on metal-on-metal hip resurfacing arthroplasty: Consensus of the 6th advanced Hip Resurfacing course, Ghent, Belgium, May 2014. *Hip Int* 2016; 26 (1): 1-7.