Hip

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Tribology of total hip arthroplasty prostheses: what an orthopaedic surgeon should know

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- Articulating components should minimise the generation of wear particles in order to optimize long-term survival of the prosthesis.
- A good understanding of tribological properties helps the orthopaedic surgeon to choose the most suitable bearing for each individual patient.
- Conventional and highly cross-linked polyethylene articulating either with metal or ceramic, ceramic-on-ceramic and metal-on-metal are the most commonly used bearing combinations.
- All combinations of bearing surface have their advantages and disadvantages. An appraisal of the individual patient's objectives should be part of the assessment of the best bearing surface.

Keywords: osteoarthritis; total hip replacement; tribology; wear

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Introduction

Although total hip arthroplasty (THA) has provided good results for over forty years, the choice of the optimal bearing surface still remains controversial. Tribology is defined as "the branch of science and technology that deals with the study of friction, wear, and lubrication".[1] Tribology is fundamental to the function and long-term survival of orthopaedic implants.

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

Following several years of investigation, Willert et al were able to demonstrate that the observed cases of aseptic loosening could be explained by a concept they described as 'particle disease'.[2] According to these researchers, polyethylene (PE) debris particles are generated in the absence of fluid film lubrication between the femoral head and the acetabular cup, due to abrasive and adhesive wear caused by the relative movements between the two surfaces. Wear particles trigger a series of biochemical reactions, which change the dynamic balance between osteoblasts and osteoclasts. The enhanced osteoclast activity results in osteolysis in the areas affected by a high number of wear particles. This resorption of bone eventually leads to aseptic loosening of implants in the long-term. Osteolysis is directly correlated with the amount of debris particles.[3-6] In order to maximize implant survival, articulating components should therefore minimize the generation of wear particles of a biologically-critical size, which is, according to Green et al, between 0.3 and 10 μm.[7]

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

Conventional polyethylenes

The MoP first used for total hip prostheses was introduced in 1962 by the British surgeon John Charnley[8] (Fig. 1). This polymer is a high molecular-weight PE with extremely long chains (between 2 and 6 million atomic mass units).

For four decades up until the mid-2000s, MoP bearings with head diameters ranging between 22 mm and 32 mm represented the 'standard' and they are still commonly used today.[9] Linear wear of MoP bearings is typically within the range of 100 to 300 μm/year.[10] This corresponds to a volumetric wear of around 20 - 150 mm^3/year for 28 mm heads.[11] Previous research has suggested that linear wear rates for 22 mm, 28 mm and 32 mm do not vary significantly.[12]

The introduction of ceramic (alumina - aluminium oxide [Al_2O_3]) heads reduced the PE wear by approximately 50%.[13] For 28 mm diameter heads this resulted in a reduction of volumetric wear by approximately 75%, with values between 5 mm and 50 mm^3/year.[11]

A study by Orishimo has shown a high correlation between volumetric wear and the risk of osteolysis for articulations using conventional PE.[6] It was reported that

Fig. 1 Charnley's metal-on-polyethylene hip arthroplasty.

every increase in the amount of volumetric wear of 40 mm^3/year triples the long-term risk of osteolysis.

Highly cross-linked polyethylenes

Highly cross-linked polyethylenes (HXLPEs) were developed in the 1990s. The cross-linking of polymer chains by forming bonds between them allows the modification of the molecular structure of the PE. This new structure leads to a significantly higher resistance against abrasive and adhesive wear.[14] Cross-linking is achieved by irradiation using either electron beams or gamma rays. For both methods, the cross-links are formed by the reaction of the free radicals that are generated by the irradiation.[14] However, once the cross-linking is achieved, it is of particular importance to eliminate, as far as possible, residual free radicals left over from the process in order to minimise the risk of long-term oxidation.[15] Several approaches are used to remove the free radicals. These include re-melting or thermal annealing treatments in the case of the first generation of cross-linked PEs.[16]

The first generation of HXLPE became clinically available at the end of the 1990s. Initial clinical studies have shown a significant decrease of wear, with reported linear wear rates ranging from between 2 and 20 μm/year, and volumetric wear rates substantially lower than 1 mm^3/year for 28 mm prosthetic femoral heads.[17-20] Since aseptic loosening after THA is rare, survival advantages of HXLPE will inevitably need to be determined in large cohorts, and long observation periods will be required. Recently, the Australian National Joint Replacement Registry reported a significantly lower revision rate for HXLPE compared with standard PE for metal-on-HXLPE, and the 14-year cumulative revision rate decreased from 9.9% to 5.4%. For ceramic-on-HXLPE the ten-year cumulative revision rate decreased from 7.0% to 4.6%.[9] The considerably reduced wear has also allowed an increase of the articulation diameter of the metal prosthetic heads up to 40 mm. *In vivo* studies have shown that linear wear is virtually independent of the articulation diameter. However, volumetric wear increases with head size.[11] Table 1 demonstrates that volumetric wear increases as a function of the articulation diameter, and that the Metal-on-HXLPE articulation with larger diameters (40 mm and larger) should only be considered for patients where the benefits of a larger diameter head (e.g. reduced risk of head dislocation) outweigh the potential risks associated with an increased volumetric wear rate.

Following reports in several publications that HXLPEs of the first generation (especially those having undergone thermal treatment) can exhibit signs of oxidation,[21] HXLPEs treated with vitamin E were recently introduced (Fig. 2).

Due to its being a highly effective free radical scavenger, Vitamin E helps to neutralise the formation of free radicals responsible for oxidation.[22] Vitamin E can be incorporated either by diffusion, or by blending it into PE before the moulding process.

Metal-on-metal bearings

With a first implantation in 1938 by Wiles, the MoM articulation was the first bearing used for THA.[23] Between the 1950s and 1970s, a cast CoCrMo alloy was used widely for these bearings. Primarily due to poor manufacturing tolerances, this historical bearing yielded largely unsatisfactory

Table I. Volumetric wear corresponding to a linear wear of 10 μm/year, as a function of articulation diameter

Articulation diameter	Volumetric wear corresponding to a linear wear of 10 μm/year[11]
28 mm	≅ 0.25 mm^3/year
32 mm	≅ 0.30 mm^3/year
36 mm	≅ 0.40 mm^3/year
40 mm	≅ 0.50 mm^3/year

Fig. 2 Highly crosslinked polyethylene insert treated with vitamin E.

clinical results (elevated wear and friction). In the 1960s, the McKee-Farrar MoM THR was introduced.[23] Due to bearing irregularities as well as impingement, the system had a higher early failure rate than the Charnley prosthesis, which was based on a MoP articulation. However, at 20 years' follow-up the survival rate of the Charnley prosthesis did not exceed that of the McKee-Farrar any longer, with 73% *versus* 77% survival, respectively.[24]

In the early 1980s, the first findings from surgeons reporting excellent clinical results with a MoM articulation were published.[25] The analysis of retrieved MoM bearings showed that articular clearance was the key factor.[25,26] Optimal clearance helps to enhance lubrication, which minimizes wear.[26] Equatorial contact, increased frictional torque, and jamming have been reported within MoM bearings designed with a low clearance,[27] and it is associated with acetabular loosening.[28,30] A high clearance, on the other hand, leads to an increase of contact pressure within the bearing, which results in an increase in volumetric wear.[31] This increase in debris can provoke metallosis.

Failure analysis of the ('first generation') MoM implants led to a greater understanding of design considerations. This, together with further improvements in manufacturing, in 1998 encouraged Weber et al[32] to develop a second generation of MoM articulations with a diameter of either 28 mm or 32 mm (Fig. 3).[25]

Good results have been reported with this articulation. Innmann et al reported 90.9% and 98.9% survival with revision for any reason and revision for aseptic loosening as end-points, respectively, at 13 years' follow-up,[33] Randelli et al reported 94% survival with revision for any reason as the end-point at 13 years' follow-up,[34] and Lass found a cumulative survival rate of 93.0% at 18.8 years, with aseptic loosening as the end-point.[35]

Based on the good clinical results of these small diameter MoM bearings (volumetric wear in the range of 0.5 mm^3/year), large diameter MoM articulations were developed for resurfacing-type prostheses as well as for total hip replacement implants in the early 2000s. Mediated by good lubrication, these MoM articulations with large diameter yielded excellent results in the laboratory.[26] However, the good *in vitro* findings did not translate into good clinical results. *In vivo*, lubrication may be insufficient due to poor positioning and/or poor design of the acetabular cup, which increases wear and friction of the articulation.[36] As a result, National Joint Registry data have shown that large diameter MoM hip arthroplasties and resurfacings with MoM bearing surfaces have significantly higher revision rates compared with those with conventional bearings.[37] The use of these articulations has been associated with wear-related adverse events, such as soft tissue inflammatory reactions to metal debris, which are summarized under the name 'adverse reactions to metal debris (ARMD). Inflammatory pseudotumours, aseptic lymphocytic vasculitis associated lesions (ALVALs) and metallosis are all examples of ARMDs. The spectrum of ARMD is wide and ranges from small asymptomatic cysts to large soft tissue masses (pseudotumours).[37]


Fig. 3 Second generation MoM articulation.

Ceramic-on-ceramic articulations

After MoM, ceramic-on-ceramic (CoC) articulation, developed in France by Boutin in 1970,[38] was the second 'alternative' bearing (Fig. 4) to the MoP bearing.

Alumina and zirconia (zirconium oxide [ZrO_2]) ceramic have historically been used in THA, with alumina being the most frequently used of the two. Alumina has a very low friction coefficient, making it an appropriate choice for an orthopaedic bearing surface. In addition, alumina is biocompatible, and *in vivo* its material properties are not affected by ageing. *In vitro* studies have shown that this articulation also offers the benefit of significantly reducing volumetric wear (within the range of 0.1 mm to 1 mm^3/year).[39-41] However, under microseparation conditions one study showed that the wear rate increased to almost 2 mm^3/million cycles.[36]

Due to the brittle nature of the alumina components and the catastrophic consequences of a possible fracture with the generation of a large number of small alumina fragments, the use of alumina-on-alumina bearings was not widespread until the early 2000s when the new composite ceramic Biolox Delta (CeramTec; Plochingen, Germany) was introduced. This ceramic is composed of 82% alumina and 17% zirconia (volumetric composition) and has twice the tenacity (resistance to crack propagation) of pure alumina.[42] This higher tenacity greatly reduces the risk of *in vivo* fracture. Fracture rates of the femoral head have reduced from 0.021% for alumina-on-alumina (Biolox Forte, Ceramtec; Plochingen, Germany) to 0.003% for Biolox Delta.[43] The fracture rate of cup inserts has remained virtually unchanged, however, at a rate of 0.03%.[43] An *in vitro* study has shown that Biolox Delta has a wear rate < 0.25 mm^3/million cycles, even under microseparation conditions and independent of cup abduction angle.[36]

Fig. 4 CoC articulation.

In spite of its higher fracture-resistance, the use of zirconia as bearing material is less widespread, since alumina is chemically more stable *in vivo*.

Excellent long-term clinical results have been reported for alumina CoC, with a cumulative survival rate of 99% at ten-year follow-up,[44,45] and with 84.4% survival after 21 years.[46] Good results have also been reported in young patients (< 30 years) without osteolysis, loosening, fractures, or squeaking at a minimum follow-up of 4.5 years.[47,48] Moreover, an *in vitro* study found that large diameter CoC articulation (up to 48 mm) does not result in higher wear rates compared to small bearings (up to 32 mm), and wear rates remained low even under edge-loading conditions.[49] Therefore, latest-generation CoC bearings allow a decrease in the thickness of acetabular components. Because of these advantages, their use has been supported in a patient population requiring large-diameter femoral heads,[50] although it still remains essential that malpositioning is avoided.[49] First results from the Australian National Joint Replacement Registry confirm that at five years' follow-up, the revision rate of large-diameter CoC articulations is not inferior to the revision rate of the 32 mm heads.[9]

Noises such as clicking, grinding, clunking, scraping, and squeaking have been reported in the literature as adverse events after CoC implantation, with squeaking being the most common. The reported incidence of squeaking varies between 0.7 – 20.9% of patients,[51] with a meta-analysis revealing 2.4% as pooled incidence.[52] Although the underlying pathomechanics are not completely understood, causative factors mentioned in the literature are sub-optimal component design, insufficient lubrication, edge-loading wear or micro-separation and inadequate component alignment.[53] Squeaking noises may lead to decreased patient satisfaction, and even to revision.[51] Owen et al reported a revision rate for squeaking of 0.2%.[54]

Ceramic-on-metal articulations

The use of a low-wearing ceramic-on-metal (CoM) articulation within THA was first reported by Firkins et al in 2001.[55] The differential hardness of the bearing partners was thought to reduce the squeaking issues found with CoC bearings, as well as the wear-related adverse events found with MoM articulations. CoM bearings have low *in vitro* wear, but *in vivo* studies seem to indicate that the post-operative serum ion levels of this bearing type are still significantly elevated,[56,57] and it remains to be seen whether this bearing type therefore, in the light of the remaining fracture risk for the ceramic femoral head component, yields any advantages over MoM bearings.

Conclusions

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

At present, it is possible to make the following general recommendations for bearing surfaces. Bearing surfaces with standard PE are still considered good options that perform very well in elderly, low-demand patients who have a life expectancy of < 15 years,[58] while alternatives have emerged for younger, higher-demand patients.[16]

While MoM articulations with small head diameters (28 and 32 mm) presented good long-term clinical results, clinical issues with larger diameter heads shed bad light on the whole technology such that MoM articulations are not expected to be used on a large scale in the future. According to Migaud et al, the only exception for active patients might be resurfacing arthroplasty, for which there are currently no credible alternatives to MoM bearings.[59]

CoC bearing combinations yield good clinical results and therefore remain a viable option in the younger and more active patient population. Due to its wear characteristics, CoC is particularly suitable for patients requiring large femoral head diameters (40 mm, 44 mm and 48 mm).[9]

The consequences of CoM bearings are unclear, as it remains to be seen whether this bearing type, in the light of the remaining fracture risk for the ceramic femoral head component and elevated wear as seen in *in vivo* studies,[56,57] yields any clinical advantages over MoM bearings.

A bearing combination comprising HXLPE with either a metal or a ceramic head offers a highly promising bearing solution that displays low wear, while being more forgiving (for the cup positioning) than alternative bearings. This technology makes it possible to minimize the risk of revision after ten years or more, and allows the use of prosthetic femoral heads with diameters that have a low dislocation rate (32 mm or 36 mm). However, HXLPEs with already-published risks of oxidation (especially those having undergone a thermal treatment) should be used with caution in order to avoid possible long-term failure. The choice of whether to use HXLPE in combination with a metal or a ceramic head is secondary, as similarly low revision rates have been obtained with both bearing materials.[9] More recently, the enhancement of HXLPE with vitamin E shows high fatigue strength, which may potentially lead to a further decrease in PE wear.[22] Although early results are promising, longer follow-up and large study cohorts will be required to determine if these will translate into improved clinical performance and durability of these implants.[60]

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