(iv) Bearing surfaces in the young patient: out with the old and in with the new?

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Summary
Total hip arthroplasty has been one of the most successful orthopaedic operations over the last half century, reducing pain and restoring function to millions of patients all over the world. This success has led to younger patients hoping to benefit. There is an increasing range of implant designs and bearing surface choices available for this challenging group of patients.

Metal on ultra high molecular weight polyethylene (UHMWPE) remains the gold standard but predictably fails by way of osteolysis secondary to polyethylene wear, particularly in the active patient. This has prompted a resurgence in the development and use of the previously tried but forgotten ceramic and metal articulations, as well as the advent of the new highly-crosslinked polyethylene (PE). It is these bearing surface options that are discussed in this review.

Introduction
Total hip replacement (THR) has been in use for over four decades significantly improving patients’ pain and function. The success of this procedure has led to the indications becoming broader and ever younger, more active patients now present for surgery.

The main limit to the longevity of these implants is aseptic loosening with osteolysis. Originally believed to be secondary to the bone cement used in the early hip arthroplasties, only later was polyethylene (PE) debris found to be the root cause. It is now widely recognised that sub-micron particles of PE initiate and maintain a predominantly macrophage driven inflammatory reaction that results in an osteoclastic resorption of periprosthetic bone. This can lead to painful loose implants requiring revision procedures in the presence of reduced bone stock, or may even present with periprosthetic fractures secondary to silent, asymptomatic loosening.

Studies have shown that the rate of wear of PE is not related to the length of time an implant has been in situ, but instead to the activity levels of the patient. In general patients’ activities reduce by 15–20% for each advancing decade of life, so they are well suited to the older patient.
By continuing with traditional hip replacement bearing surfaces in young active patients they may well require multiple revision operations with all the associated risks.

This review looks at the evidence for the currently available bearing couples, including metal-on-metal, ceramic-on-ceramic, metal-on-newer highly-cross linked polyethylene and metal-on-ceramic articulations.

Basic science

It is PE wear that results in implant failure, so we must consider the mechanisms of wear in order to understand the interest in newer bearing options.

Friction

Friction is generated when two surfaces are in contact, and is best demonstrated by trying to slide these two surfaces against each other. The force is proportional to the normal load applied to the surface and the coefficient of friction, but is not affected by contact surface area. The coefficient of friction is determined, in part at least, by the bearing surface material.

There are two coefficients of friction, static and dynamic. It requires a greater force to initiate sliding than to maintain it, so the latter is generally considered to be 70% of the former. An analogy would be the speed skater who needs to work very hard to get up to speed, but can then maintain it with apparent ease.

The contact area also determines the frictional force. The true contact area for many bearing surfaces is far less than the apparent contact area, somewhere in the region of 1%. This is due to the marked irregularity of the surfaces (asperities) at microscopic level. Only very small peaks from each surface contact each other. This increases the force significantly at these points of contact and causes the two surfaces to bond. In order to initiate sliding these bonds need to be broken, thus explaining the higher force required to initiate over maintaining movement.

Friction also results in the transfer of force from the articulating areas to the fixed interfaces, for example frictional torque can be transferred to the acetabular component from the friction generated in the artificial hip. This led to the early use of small femoral heads. As manufacturing tolerances improve, and newer bearing couples are designed, the aim is to reduce the friction experienced between surfaces and allow larger femoral head sizes.

Lubrication

In both the human body and artificial joints two surfaces never articulate without some form of lubrication, which significantly reduces frictionally generated torque between them. Friction occurs when two surfaces contact resulting in small bonds forming between them. Fluid lubrication can separate the surfaces, thus reducing the friction. This can happen in a number of different ways, and is influenced by the bearing materials.

Boundary lubrication

This occurs when the fluid layer is only a few molecules thick and the asperities still touch. It is not ideal and is more likely to occur in rough bearing surfaces, or as a result of third body formation or protein deposition. It is improved with better manufacture tolerances of the bearing surfaces. The longer implants remain in situ the more likely they are to develop this type of lubrication.

Hydrodynamic lubrication

This occurs when the surfaces are completely separated by lubrication fluid and is divided into two groups depending on whether the two surfaces are conforming or not. Native joints are conforming (hydrodynamic lubrication) unlike artificial joints that deform elastically (elastohydrodynamic lubrication).

The thickness of the lubrication fluid depends on a number of factors:

- Viscosity
- Sliding velocity (velocity at which the fluid is forced into gaps)
- Applied stress.

This is expressed as a Sommerfield number. The higher the value, the thicker the lubrication film.

Sommerfield number \( \times \frac{\text{Fluid viscosity} \times \text{sliding velocity}}{\text{Applied stress}} \)

The wettability of the materials also plays a part. This is essentially describes how hydrophobic or hydrophilic they are. The ceramics are the most wettable of the currently used bearings.

During walking there are two other forms of lubrication that occur in weight-bearing joints.

Weeping

Fluid contained within the hyaline cartilage is forced out to add to the fluid layer between the joint surfaces during the weight-bearing phase. This helps keep the surfaces apart.

Squeeze film

As the leg is lifted in swing phase, thus reducing the force across the joint, fluid is sucked back to the area between the joint surfaces. Fluid can then return to the hyaline cartilage.

There is a third type of lubrication known as hydrostatic lubrication, but this does not occur in nature as it relies on a pump to maintain the fluid layer.

Each of the different bearing surfaces available influence the type of lubrication that occurs within an artificial articulation, therefore different types of wear can occur.

Wear

Wear occurs due to movement between two surfaces in contact. In general the softer of the two materials wears more quickly, as seen in the traditional metal-on-UHMWPE. This generates debris particles. Once again there are a number of different wear patterns, as described below:
Mechanical wear

Adhesive wear
The bonds that form between surfaces need to be broken to allow movement. If the bonds are the weakest point then they will break. Sometimes one of the materials is weaker than the bonds so it breaks preferentially. Thus a layer of the weaker material lines the stronger material, changing the interface at which movement takes place. The bonds that form remain stronger than the material so fragments of the material are broken off. This is termed third body wear.

Abrasive wear
It occurs when the asperities and imperfections of the harder surface damage the softer surface. This is accelerated with the presence of debris. Modern machining can help reduce this process.

Fatigue wear
It occurs within materials due to repeated cyclical loading. Usually cracks appear next to areas where apparent contact occurs. In essence there is a difference in the load experienced by two adjacent areas of the same material which gives rise to fatigue failure.

Fretting wear
It tends to occur as a result of high loading at interfaces with minimal movement, particularly at modular connections. Small amounts of debris occur but due to the small movement present these cannot escape so accelerate the wear in an abrasive fashion.

Corrosive wear
This is a form of chemical wear and often it works in synergy with the mechanical wear mechanisms. Oxidation of the bearing surfaces results in them becoming more brittle, which in turn propagates the mechanical wear. As the surface is eroded in this manner, the oxidation process can extend further into the material perpetuating the process.

Osteolysis

Osteolysis is a significant cause of aseptic loosening and is the biggest cause of revision surgery. It is due to resorption of bone, which is seen more commonly around the acetabulum than the femur. There is a link between wear and corrosive debris formation and osteolysis and is seen more commonly in patients with high wear of their implants. It is often seen as lucency around the implants on radiographs taken years after the original procedure, but can be underestimated on plain films.

The primary cellular mediator is the macrophage. In the presence of debris it produces a number of cytokines and inflammatory mediators (IL-1, IL-6, IL-10, TNFα and prostaglandins). These initiate increased osteoclast activity and also increase osteoclastic differentiation, whilst the debris particles actually have a detrimental effect on osteoblastic bone formation. This clearly results in a mismatch. Within osteolytic areas other cell lineages may be found including fibroblasts and lymphocytes. Both of these contribute to the ongoing osteoclastic activity and periprosthetic bone resorption (Fig. 1).

It is now becoming evident that the size of the wear particles is of equal importance to their number. Nanometer particulate wear debris does not appear to affect the osteoblasts significantly, and coupled with a lower wear rate longer implant survival could be predicted.

As the bearing surfaces clearly have an effect on implant survival, it is important to consider the different pairings and look at the relative merits of each. Charnley started using metal-on-PE THR in 1962 (having tried Teflon unsuccessfully) followed by others (Exeter 1970). Notwithstanding early cementing techniques, the survivorship of these implants has been very impressive — the 20 year survival for the Charnley being 83%. However, looking at younger patients as a subgroup shows that if the

![Figure 1](image_url) Radiograph showing osteolysis around femoral stem (red arrows) associated with eccentric wear of the polyethylene acetabular component (black arrows).
THR is implanted at 40 years or younger the survivorship is 67% (compared with 92% if aged 70 or over). Exeter have recently published figures for under 50 years (mean 42) showing 92% survival at 12 years. The difference is due to higher activity levels in younger patients rather than the length of time the implant has been in situ. Numbers from the Norwegian Hip Register show that between 1987 and 2000 85% of all THR implanted were metal/UHMWPE, but by 2001–2006 this had reduced to 65%. The <60 age group had 51% (of 4631) from 1987–2000 and 38% (of 7403) during 2001–2006. In this age group more metal-on-metal, ceramic-on-ceramic and ceramic on UHMWPE implants were being used. The register does not yet report survivorship statistics for surface bearings.

**Metal-on-polyethylene**

As with all orthopaedic implants the manufacturing standards and methods are critical to the success of metal-on-UHMWPE surface bearings. For over 20 years direct moulding has been used. Polyethylene powder is heated and pressed into moulds to form the implant. Moulding lowers the elastic modulus which helps to create larger contact areas and lower stresses, and also gives better resistance to wear damage.

The most common method of sterilization was by gamma irradiation in air, which gave rise to free radicals. In the presence of oxygen these combine, resulting in chain scission - the shortening and fragmentation of the long chains - causing sub-surface oxidation and fatigue cracking and lamination. Additionally after implantation any free radicals near the bearing surface would react with oxygen within body tissues causing further chain scission nearer the surface of the implant, changing the wear characteristics of the polyethylene at different depths of the implant.

Early attempts to remedy this was by sterilization in a nitrogen atmosphere and by increasing the crystallinity of the polyethylene. Crystallinity is the percentage by weight of the crystalline phase present in the whole polymer. In the case of Hylamer polyethylene the crystallinity was increased from 50% to 70% to try to improve the wear characteristics. This worked well in vitro but showed dramatically different characteristics in vivo. The polyethylene particles from the Hylamer were larger, more elongated and more prevalent than those of conventional UHMWPE. This led to premature failure with massive osteolysis due to increased macrophage activation. This and a number of other factors contributed to the catastrophic failure of this type of polyethylene.

If the shelf life (time from manufacture to implantation) was more than 10 months linear wear was 0.23 mm/year, compared with 0.05 mm/year if shelf life was less than 10 months and Gamma irradiation in nitrogen rather than air decreased the wear from 0.23 mm/year to 0.09 mm/year.

This failure demonstrated that in vitro testing does not accurately predict in vivo characteristics and also that small changes to manufacture can lead to disastrous results.

Overall however, conventional metal-on-UHMWPE bearing surfaces have stood the test of time. They are relatively cheap and predictable to manufacture. Their mode of failure is well known and gradual and despite evidence of systemic distribution of UHMWPE particles there are no clinically apparent systemic consequences.

- Excellent results in young patients
- Long follow-up
- Cheap
- Oxidation risk if long shelf-life

**Metal-on-metal (MOM)**

With the success of metal-on-UHMWPE, metal-on-metal (MOM) THR lost favour. The problems with MOM were assumed to be due to the unsuitability of metal on metal as a bearing pair. However, the problem was unreliable manufacturing causing premature wear, implant failure and loosening. The prostheses that were manufactured well showed comparable results to the Charnley THR. The 20 year survival of the MOM McKee Farrar THR was 84% and retrieval studies have shown that MOM prostheses produce substantially less wear than metal/UHMWPE. The number of particles generated by MOM surfaces is considerably more than metal/UHMWPE (approximately 13500x the amount) but they create much less volumetric wear because their size is so much smaller (<50 nm compared to 0.1 μm for UHMWPE); hip simulator studies have shown up to a 200-fold reduction in volumetric wear rates compared with UHMWPE articulations. Due to their size the extent of their dissemination around the body is not yet known.

The type of materials, head diameter and radial clearance, surface topography and lubrication influence the wear of MOM bearings far more than metal/UHMWPE bearings. Mixed film lubrication appears to be the main mechanism in most MOM hips, but fluid film lubrication is encouraged by increasing the diameter of the femoral head (by increasing the sliding velocity thereby pulling more fluid into the articulating surface). The increase in head size also has the additional benefit of decreasing the wear rate. The results for metal-on-metal THR compare very favorably with other bearing surfaces (100% 10 year survival with endpoint revision of either component in under 50 year olds).

For younger patients attempting to preserve femoral bone stock for probable future revision THR is highly desirable. Resurfacing arthroplasty using MOM addresses this and also avoids long-term stress shielding, which can lead to bone resorption and implant loosening. The large diameter of the articulation offers increased stability and range of movement. While resurfacing started in 1948 and despite the advances up until the 1980s the materials, implant design and poor instrumentation meant that the procedure was abandoned. Its re-emergence is due to much improved manufacturing quality, improvements in instrumentation and surgical technique due to understanding of hip biomechanics and femoral head/neck blood supply. Long term results are not yet available but recent independent series show a 95% survivorship at 7 years (Fig. 2).

There are concerns regarding the potential toxicity of metal wear debris. Free or phagocytosed wear particles are
transported within the lymphatic system. Metallic debris may also distribute through the vascular system as ions or particles. Reported blood levels of Chromium (Cr) four years post MOM THR are between 4.6 μg/L and 6.5 μg/L. The Health and Safety Executive have guidance values for chromium of 17 μg/L in blood and 20 μg/L in urine and several studies have shown higher levels than this in patients following MOM THR. Very little data exist for systemic effects of MOM wear particles but virtually every organ in the body has potential toxic responses, for example altering the function of B cells, T cells and macrophages, hepatocellular necrosis, impaired renal function, increased incidence of asthma, memory loss and ataxia, cardiomyopathy and pathological fractures. An increased incidence of chromosomal aberrations has been found in the peripheral lymphocytes of arthroplasty patients. There is a growing consensus that metal-induced DNA damage may lead to carcinogenesis. Occupational metal exposure, such as to Cr, has been linked to an increased risk of cancer. Chromium and cobalt are also able to cross the placenta with levels of cobalt significantly higher than controls but not for Cr, leading to concerns about implanting MOM THR in females of child bearing age. There are also small numbers of failures of resurfacing implants due to femoral neck fracture and avascular necrosis of the femoral head. These causes of failure are out with the scope of this article. Metallosis has not been recognized as a cause for failure but does make revision surgery longer and bone loss can be extensive.

In conclusion metal-on-metal as a surface bearing has demonstrated its low wear characteristics and low rate of revision for aseptic loosening but has not been able to prove its wear particles will not be carcinogenic in the long term.

Ceramics in hip arthroplasty

These are solid inorganic compounds consisting of both metallic and non-metallic elements, joined by both covalent and ionic bonds. They have a 3-dimensional structure with the positively charged metal ions surrounding themselves with as many negatively charged non-metals as possible and vice versa. This produces a tightly packed structure with a neutral overall charge, endowing ceramics with a number of desirable properties including high compressive strength, hardness, scratch and wear resistance and wettability. Ceramics have a polygranular structure, which can be influenced by manufacture. It is beneficial to keep the particles as small as possible, whilst also reducing the porosity to resist wear. There is the added benefit that ceramics appear to be biologically inert materials, unlike some of the other bearing surfaces. The main concern with ceramics is the perceived propensity for fracture due to its brittle nature. A great deal of work has been undertaken to reduce this over recent years.

There have been two main ceramics used in arthroplasty over the years. They have been used articulating with a variety of bearing surfaces, including UHMWPE, similar ceramic and more recently metal.

Alumina

This was the first ceramic to be widely used in hip arthroplasty, following its introduction in 1970. Aluminium oxide (Al₂O₃) can be highly polished to produce a very low coefficient of friction and is also highly resistant to abrasion. It has a more stable structure than the more recently developed Zirconia so the properties are more predictable. Improved manufacturing techniques have resulted in smaller grain size and smoother finish helping to reduce the fracture risk that was encountered when using earlier generations.

Zirconia

Zirconium oxide (ZrO₂) was introduced in 1985 as an alternative to alumina. Its superior mechanical strength was attractive with a theoretical reduction in fracture risk. It also allowed smaller femoral head sizes whilst maintaining excellent wear characteristics when coupled with UHMWPE. Clinical trials have shown that UHMWPE wear when coupled with a zirconia femoral head is at least as good as that with a Cobalt Chromium femoral head and in many cases is much better. However Zirconia undergoes phase transformation. The strongest tetragonal phase is also the most unstable, so a stabiliser, Yttrium oxide, is used. In vivo studies have shown that phase transformation still occurs at the bearing surface secondary to temperature and pressure changes which transforms zirconia to the more stable monoclinic phase. This results in a 3% increase in volume producing surface roughness. Hence it performs poorly when articulating against itself and can also result in accelerated polyethylene wear bearing on UHMWPE. As a result it has fallen out of favour (Fig. 3).
The proponents of ceramic bearing surfaces for hip arthroplasty in the young patient would have us believe it is the perfect option. It has all the beneficial wear and lubrication features described above, and the fracture risk has been virtually eliminated with improved manufacturing. Additionally there is increasing evidence from clinical studies that the low wear rates seen in hip simulator studies are being seen in vitro at medium-term follow up. Third generation ceramic has been shown to wear significantly less than standard UHMWPE resulting in less osteolysis and revision, with implant survival being as high as 99% when looking specifically at revision for aseptic loosening at 7 years.9,10

Ceramics have not only been used in ceramic-ceramic bearings, but also instead of Cobalt Chromium (CoCr) articulating with UHMWPE. The advantage is that the ceramic is smoother than the CoCr heads. They have a better scratch profile than the metal, when metal is scratched, 2 peaks and a trough are formed, unlike ceramic where only a trough is left (Fig. 4) resulting in less abrasive wear. Clinically a 50% reduction in wear rate is seen at medium-term follow up.2

Potential problems

Longevity of ceramic bearings is not guaranteed. There are many variables including design, fixation and also positioning; recent work has shown much more wear in ceramic implants at medium follow up if the acetabular component is anteverted by less than 15°–20°. Computer-aided surgery may have a role in reliably reducing this risk. If malpositioned then there is a risk of edge-loading and impingement of the implants, resulting in failure of fluid film lubrication and subsequent stripe wear phenomenon, which can increase the risk of ceramic fracture.11

Increasing evidence supports the theory that stripe wear may be identified by an audible squeaking from the hip, which may act as a warning for imminent head fracture.5,12

Highly-crosslinked polyethylene (A)

Standard UHMWPE has a very simple structure. It is a polymer of one of the simplest organic molecules, ethylene:

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\begin{align*}
\text{H} & \quad \text{H} \\
\text{C} & \quad \text{C} \\
\text{H} & \quad \text{H}
\end{align*}
\]

It is a very long polymer, which gives it the high molecular weight despite it having no branches. In graphic terms it can be represented as a long straight line. It is a viscoplastic solid meaning it has crystalline areas within an amorphous matrix. The importance of manufacture and sterilisation of UHMWPE properties has been discussed. In terms of manufacture, implants can either be machined from an extruded bar of UHMWPE or directly moulded to shape, all of which have effects on wear characteristics.

To address the problems of free radicals, oxidation and chain scission arising from sterilisation has led to cross-linking. This occurs when sterilisation is undertaken in the absence of air. Free radicals are produced in the same way, but in the absence of oxygen they provide energy to create links between the long crystalline PE chains oxidation and crosslinking can be considered as competing processes. Crosslinking reduces the amount of molecular mobility perpendicular to the primary molecular axis, which is of particular use in acetabular components where multidirectional shear forces are seen.
Unfortunately free radicals persist within the polyethylene and again oxidation can occur once the component is implanted. If the implant is re-melted all the free radicals are used, pushing the reaction to maximal crosslinking, but this affects the crystalline structure. Another option is the process of annealing where the polyethylene is heated to just below melting point, pushing most of the free radicals to crosslinking, while not affecting the overall structure.

Highly crosslinked PE wears significantly less than UHMWPE and less head penetration occurs in the short- to medium-term.\textsuperscript{13,14} Low wear rates in standard UHMWPE have shown reduced risk of osteolysis.\textsuperscript{15} Increased wear resistance allows a larger femoral head to be utilised, as the polyethylene does not need to be as thick, which has the benefit of reducing the risk of dislocation in the fit and active younger patient (Fig. 5).

However despite recent clinical data showing reduced wear in vivo in the short term, questions still remain. There is increasing evidence that when highly crosslinked polyethylene is annealed the remaining free radicals do cause oxidation, detrimentally affecting in vivo performance.\textsuperscript{16} This was suggested by simulator studies on retrieved implants but clinical results at up to 6 years follow-up have not reflected this.\textsuperscript{7}

The re-melted highly crosslinked polyethylene does not have problems with oxidation, but the reduced crystallinity associated with re-melting also reduces toughness, creating a potential for fatigue crack propagation and mechanical failure. Again retrieval analysis and clinical findings at 5 years do not support this.\textsuperscript{17}

Other advances

There are some laboratory and very short-term clinical data to support the use of ceramic femoral heads articulating with metal acetabular components. These appear to produce less stripe wear with edge loading than metal-on-metal implants.\textsuperscript{18} It also appears that there is a reduction in metal ions in the patients at 6 months. Though there have been reports of early catastrophic failure if this pairing is reversed and a metal head is articulated with a ceramic acetabular component.\textsuperscript{19}

Discussion

Despite huge amounts of laboratory and clinical data, there is still no clear evidence to support any one bearing pair especially for hip arthroplasty in the younger patient.

Conclusions

Hip arthroplasty is one of the great medical successes over the last half-century. Younger patients are a particular challenge as their expectation is often higher and they will have a longer period of time needing their implant. Traditional metal-on-UHMWPE have shown excellent results in this age group, and to date no other bearing surface couples have provided long enough follow-up to oust this as the gold-standard.

References


