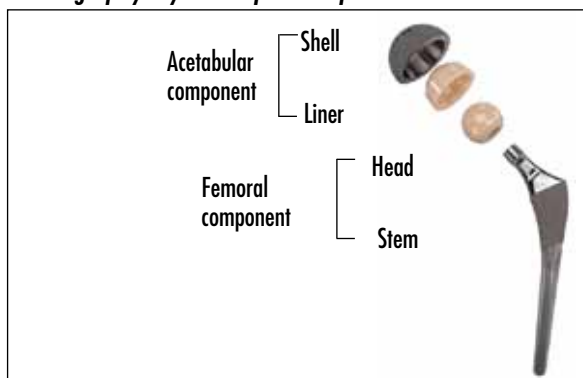


# Bearing couples in total hip arthroplasty

*Total hip arthroplasty is a well-established treatment for arthritis of the hip. The choice of bearing couple used for articulation should be tailored to the patient. This article reviews the history of different bearing surfaces, and outlines the advantages and disadvantages that may influence their use.*

Sir John Charnley, the pioneer of total hip arthroplasty, helped develop one of the first total hip replacements in the 1950s using a Teflon acetabular cup and monoblock stainless steel femoral component. Since then, there has been great evolution in tribology and component design (Figure 1). Three main categories of materials make up the artificial bearing couple: metals, polyethylenes (plastics) and ceramics (Table 1). The combination of these surfaces will contribute to the success of a total hip arthroplasty. However, there is no perfect permutation that fully replicates a disease-free, native hip.

**Figure 1. Four components make up a total hip replacement with an uncemented acetabulum. The bearing couple shown in this Exactech system exists between the ceramic femoral head and ceramic acetabular liner. In cemented acetabular components, there would be a single polyethylene component in place of the shell and liner.**



**Table 1. Possible combinations of bearing couples listed in order of decreasing popularity**

Femoral head	Acetabular articulation
Metal	Polyethylene
Ceramic	Polyethylene
Ceramic	Ceramic
Metal	Metal
Oxinium	Polyethylene
Ceramic	Metal

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The advent of national arthroplasty registries has helped develop our understanding of which prostheses are used, and when and why they fail. In the UK, the National Joint Registry of England and Wales was set up in 2002 and its 2009 annual report lists aseptic loosening as the most frequent reason (63%) for undertaking a single stage total hip arthroplasty revision (National Joint Registry of England and Wales, 2009). It is believed that the wear particles generated from the friction between articulating surfaces are the primary underlying cause for this loosening and this is an immune-mediated osteolysis process. Consequently, minimizing wear particle production may reduce the risk of aseptic loosening – little or no osteolysis will be experienced if there is less than 0.5 mm/yr of linear wear (Dumbleton et al, 2002). (Figure 2 explains linear wear.) This article explores the properties of each material and the arguments for and against each combination.

## Metals

Charnley's combination of Teflon and stainless steel quickly failed because of Teflon's poor wear properties. The generation of wear debris resulted in high rates of aseptic loosening and led to the switch to polyethylene for the acetabular surface. In combination with a 22 mm stainless steel head, this famously became known as the 'Charnley Low Friction Arthroplasty'. At a minimum 30-year follow up, the survivorship of this implant is estimated to be 87.2% (Wroblewski et al, 2009), although the choice of metal used has changed over the years.

The main advantage of stainless steel and the reason for its early use in total hip arthroplasty is its high resistance to

## Glossary of terms

Term	Definition
Bearing couple	Combination of articulating surfaces
Friction coefficient	Measure of resistance to sliding motion between two surfaces
Hardness	Ability to resist scratching and indentation
Tribology	Science and technology of interacting surfaces in relative motion
Toughness	Amount of energy that a material can absorb before failure
Wear	Erosion of material from a solid surface by the action of another surface
Wettability	Affinity of a lubricant for a material

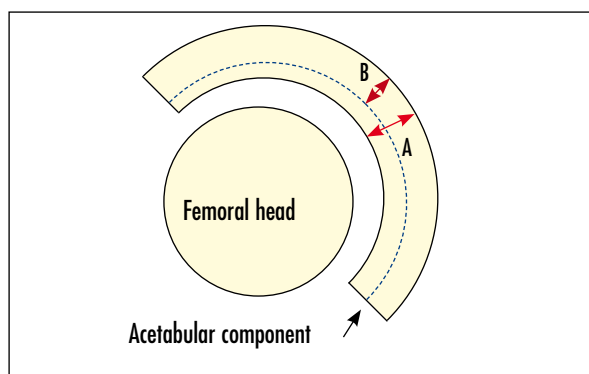
fatigue. However, it has two disadvantages: it can be corrosive, and as it is a nickel alloy it is unsuitable for the 4.5% of the population who are sensitive to nickel. Of other available metals, titanium confers good biocompatibility but has a low hardness and therefore is notch sensitive and can produce considerable wear debris. Cobalt–chrome alloy can be expensive to manufacture but has good wear properties and high tensile strength, and so it is currently the most widely used bearing surface of femoral implants (National Joint Registry of England and Wales, 2009).

Although metal-on-metal articulations have been used for total hip arthroplasty previously, sub-optimal design and high surface roughness contributed to early failure. However, improvements in the manufacturing process allow smoother surfaces and thus lower friction. Metal-on-metal has a much lower combined surface roughness than metal-on-polyethylene (roughness average =  $0.08\ \mu\text{m}$  vs  $1.29\ \mu\text{m}$ ; Scholes et al, 2000). Accordingly it is highly resistant to volumetric wear and thus permits the use of larger femoral heads including resurfacing procedures. This in turn reduces the risk of dislocation by increasing the arc of motion. With metal-on-metal bearings, volumetric wear decreases with increasing head size thereby potentiating its benefits. The main risks of metal-on-metal are:

- Long-term accumulation of metal ions
- Metallosis or metal allergy
- Aseptic lymphocyte-laminated vascular-associated lesions.

Metallosis is infiltration of metal particulate matter into local tissues with a consequent delayed hypersensitivity reaction. It tends to occur in the early postoperative period over the first few years and may cause fibrosis, osteonecrosis, pseudotumours or implant loosening. Aseptic lymphocyte-laminated vascular-associated lesions are a separate phenomenon to metallosis and occur in 1 in 500 patients. The underlying mechanisms are not yet fully understood although these lesions have been implicated in the formation of pseudotumours. These scenarios lead to early clinical failure while risk factors for this phenomenon include female gender, a

**Figure 2.** As time progresses, the femoral head will wear into the acetabular component and its thickness will change from A to B. This change in distance is linear wear. The total volume change is called volumetric wear.



small femoral component, a high abduction angle and obesity (Ollivere et al, 2009). The risks of metal ion accumulation are higher in chronic renal failure and may even predispose to malignant conditions although there is not yet any proven evidence to support this claim.

## Polyethylene

Polyethylene is the most commonly used material for acetabular articulation. The type used is ultra-high molecular weight polyethylene (UHMWPE) which is made of much longer molecular chains than standard weight polyethylene. This allows stronger interactions between chains thus conferring better longevity. A thin acetabular component permits a larger and thus more normal size of head to be used, allowing closer replication of normal anatomy and function. However, it also increases the contact surface area which will lead to more wear, so a compromise is required to minimize the risk of aseptic loosening.

There have been numerous attempts to improve the properties of UHMWPE. These include incorporation of carbon fibres (Poly II) and recrystallization (Hylamer) although both were associated with marked failure. More recently, electron-beam or gamma irradiation has been used to generate free radicals in a vacuum or inert atmosphere to increase cross linking between the polymer chains of UHMWPE. The resultant compound is called highly crosslinked polyethylene. Although Hylamer was also highly crosslinked, the generation of free radicals in the presence of oxygen rather than a vacuum lowered molecular weight and thus strength (Heisel et al, 2004).

There is increasing evidence that highly crosslinked polyethylene has a better wear resistance profile, both in terms of linear ( $0.003\ \text{mm/yr}$  vs  $0.051\ \text{mm/yr}$  with UHMWPE) and volumetric wear ( $33\ \text{mm}^3/\text{million cycles}$  vs  $71\ \text{mm}^3/\text{million cycles}$  with UHMWPE), without compromising functional outcome (McKellop et al, 1999; Digas et al, 2007; McCalden et al, 2009). Despite its superior wear resistance, mechanical failures were reported with first generation highly crosslinked polyethylene and it was thought that residual free radicals caused oxidative chain scission over time and thus structural deterioration (Collier et al, 2003). This led to the development of second generation highly crosslinked polyethylene materials which were enhanced either sequentially, mechanically or with vitamin E. It is believed that they have better fatigue properties as they contain fewer free radicals but the cost effectiveness is yet to be proven.

## Ceramics

Ceramics are inorganic, crystalline materials and alumina and zirconia are the most widely used for modern hip arthroplasty. Data pooled across multiple joint registries demonstrate that although metallic heads are currently preferred over ceramic overall, there is an increasing trend to use ceramic heads; an alumina head in conjunction with a polyethylene liner is seeing the greatest rise in popularity (National Joint Registry of England and Wales,

2009; Nasjonalt Kompetansesenter for Leddproteser, 2009). Ceramic heads on metal cup combinations have also been used which produce a lower wear volume in vitro ( $0.01 \text{ mm}^3/\text{million cycles}$ ) than metal-on-metal combinations ( $1.23 \text{ mm}^3/\text{million cycles}$ ) (Firkins et al, 2001). An in-vivo study found significantly reduced production of chromium ions at 12 months (Isaac et al, 2009) and thus may present a relative compromise to metal-on-metal with respects to the side effects of metallosis.

### Alumina

Alumina (aluminium oxide) was first used for total hip arthroplasty in the 1970s by Pierre Boutin and continues to be popular for its wear profile. Ceramic couples have a reduced coefficient of friction compared to metal-on-polyethylene or metal-on-metal, while ceramics have a low surface roughness in the range of  $0.007\text{--}0.02 \mu\text{m}$  (Boutin et al, 1988; Kim and Kim, 2008), are very hard and have excellent biocompatibility. In addition, ceramics have better wettability than cobalt-chrome with a lower surface contact angle of  $44^\circ$  (which promotes lubrication) compared to  $87^\circ$  (Boutin et al, 1988). All these factors contribute to the superior wear resistance that has been seen in both laboratory and in-vivo studies. In hip simulator studies alumina-on-alumina articulations produce very low wear rates of  $0.04 \text{ mm}^3/\text{million cycles}$  compared to  $5.62 \text{ mm}^3/\text{million cycles}$  of alumina-on-highly crosslinked polyethylene couples (Essner et al, 2005).

Initially, industrial standard alumina was used but when implanted in patients it was associated with catastrophic fracture rates as high as 13.4% (Knahr et al, 1987). Changes in manufacturing techniques have improved the properties of alumina, such that third-generation alumina has been used since 1990. These alterations include reducing grain size, increasing purity and using hot isotactic pressing to increase density, and have improved survivorship with lower reported incidences of component fracture.

In England and Wales, 1% of primary total hip arthroplasty procedures fail as a result of femoral head fracture (National Joint Registry of England and Wales, 2009). Although it is not known which materials make up these prostheses, it is likely that these were nearly all ceramic since fracture of metal prostheses is rare.

Survivorship of alumina-on-alumina bearing couples overall is at more than 91% in patients younger than 40 years and 96% of patients older than 40 years at a follow up of 80 months (Garcia-Rey et al, 2009). However, in very young adults (less than 30 years of age), survivorship has been reported at 82.1% at 10 years dropping to 72.4% at 15 years (Nizard et al, 2008). The lower rate in younger patients is likely attributable to greater activity and demand on the bearing surfaces.

Aside from fracture, there is a variable incidence of audible squeaking in ceramic-on-ceramic couples, reported to be as low as 0.63% (Walter et al, 2004) but also as high as 21% (Keurentjes et al, 2008). The cause is not fully understood although it is thought that the sound

arises as a result of roughening of the articular surfaces. This is observed during revision total hip arthroplasty as stripe wear on the femoral head and can arise from edge loading or subluxation. This is evidence that these are much less forgiving than metal-on-polyethylene articulations, so accurate component position is crucial to avoid impingement. Increased anteversion may reduce the risk of stripe wear (Walter et al, 2004; Lusty et al, 2007).

### Zirconia

Zirconia (zirconium dioxide) is a newer ceramic that was introduced as an alternative to alumina to overcome the risk of fracture. It was desirable because of its increased toughness and strength bending compared to alumina. These properties are partly a result of the phase transformation it exhibits. Pure zirconia can exist in either a cubic, tetragonal or monoclinic structure depending on temperature ( $>2370^\circ\text{C}$ ,  $1170\text{--}2370^\circ\text{C}$  and  $<1170^\circ\text{C}$  respectively). The monoclinic structure is not sufficiently strong to allow it to be used continuously in that phase. Yttrium oxide is thus added to stabilize zirconia in the tetragonal phase and prevent it transforming under normal physiological loading. However, when under stress, it transforms to the monoclinic phase. This is accompanied by a 3% increase in volume which reduces the propagation of any surface cracks and explains its superior fracture toughness.

Although surface roughness is similar to alumina at  $0.007\text{--}0.02 \mu\text{m}$ , hip simulator studies show an improved volumetric wear profile ( $0.013 \text{ mm}^3/\text{million cycles}$  with zirconia-zirconia articulations,  $0.014 \text{ mm}^3/\text{million cycles}$  with zirconia head-alumina cup articulations; Clarke et al, 2000) and superior wear resistance compared to alumina when articulating against UHMWPE (Kumar et al, 1991). However, simulator results should be interpreted with caution since artefactual coatings formed by serum can give erroneous results on wear properties.

Zirconia articulations have been around for two decades but few long-term studies have been published and data are conflicting. Inoue et al (2006) reported a minimum 10-year follow up of zirconia-UHMWPE *vs* cobalt-chrome-UHMWPE, where the average annual linear and volumetric wear was about two-fold greater with zirconia than with cobalt-chrome. This is similar to work by Hernigou and Bahrami (2003) who compared both alumina and zirconia with stainless steel femoral heads using a polyethylene liner, again at a minimum follow up of 10 years. They found that zirconia performed badly in terms of polyethylene wear compared to stainless steel and alumina. However, retrieval of explanted alumina and zirconia heads has shown similar amounts of roughness and UHMWPE penetration after approximately 10 years for both (Kim and Kim, 2008).

Mid-term follow up of approximately 5 years also show varied results, with zirconia producing either more polyethylene wear than alumina (Liang et al, 2007) or stainless steel (von Schewelov et al, 2005), or equal to (Kraay et al, 2006) or less than cobalt-chrome (Kim, 2005).

Zirconia's poor longer term performance could be a result of the transition to monoclinic phase where the volume increase can increase surface roughness leading to excessive wear. In addition, variations in the composition of zirconia heads between manufacturers could be responsible for the variability of results seen in patient studies.

## Hybrid technology

### Oxinium

Oxinium (Smith & Nephew, Warwick, UK) is a recently introduced material that has mixed properties as a result of its composition. It is composed of an oxidized zirconium–niobium metal alloy that is heat treated. This produces a head with a metal core but an oxidized zirconium surface of up to 10 µm thick which maintains ceramic-like surface properties (D'Antonio and Sutton, 2009). In-vitro work by Good et al (2003) demonstrated 'undetectable' levels of volumetric wear with Oxinium and highly crosslinked polyethylene couple although this was not reproduced when using UHMWPE instead of highly crosslinked polyethylene. This is supported by in-vivo radiostereometric analysis using the same couple at 1 year follow up (Li et al, 2006). A clinical study of follow up at 2 years has shown that functional outcomes and survivorship is comparable to cobalt-chrome although in-vivo wear patterns have not yet been established (Lewis et al, 2008). Further randomized studies will demonstrate whether the anticipated benefits are reproduced in vivo.

### Femoral head size and friction

As well as the material used in the bearing couple, the sizes of femoral head can also influence the amount of wear. Charnley chose a 22 mm head as a compromise between function, friction and wear. A larger head size produces less linear wear but increased volumetric wear. Consider Archard's equation:

$$\text{Volume of wear} = \frac{\text{constant} \times \text{normal load} \times \text{sliding distance}}{\text{Hardness of material}}$$

Since polyethylene is softer than ceramic or metal, a thicker acetabular cup is required which limits the femoral head size. However, development of highly crosslinked polyethylene has allowed for a thinner cup and thus larger head size without compromising wear up to certain limits.

The advantages of an increased head size, as used with metal-on-metal resurfacing, is a closer replication of normal hip function and motion, and a lower rate of dislocation. With ceramics, lower rates of component fracture have been reported in larger heads (D'Antonio and Sutton, 2009). Severe damage meanwhile has been reported to the surface of Oxinium head when dislocation has occurred (Evangelista et al, 2007). All this supports the use of large heads although this must be balanced against wear of the acetabular component.

Another influence of wear particle formation is the friction that occurs between the bearing couples. *Table 2* shows that a native hip produces the least amount of friction while metal-on-metal couplings produce a high friction

coefficient. Although one might think that a high friction coefficient is associated with high wear, metal is much tougher than UHMWPE and thus more resistant to wear.

### Cost effectiveness

The long-term failure rates of newer bearings need to be much lower to offset the higher costs. Faulkner et al's (1998) model compared prosthesis cost, revision rates and expected total costs to show that alumina–alumina combinations are still more expensive over 20 years compared to conventional bearings overall. However, by analysing different demographic groups, Bozic et al (2006) suggested that hard-on-hard bearings are more cost effective if implanted into patients younger than 63 years, whereas metal-on-polyethylene couples are better for older patients.

### Conclusions

The various combinations of bearing couples all have advantages and disadvantages. Reducing wear particle production will improve the long-term survival of the total hip arthroplasty prostheses and the recommendation for the 'best' articulating combination will vary according to patients' needs.

Cobalt-chrome in combination with polyethylene (either highly crosslinked polyethylene or UHMWPE) is currently the default bearing couple although mounting evidence regarding the superior performance of highly crosslinked polyethylene will likely see a gradual phasing out of conventional UHMWPE.

Metal-on-metal articulations are ideal for hip resurfacing and thus commonly used in young, healthy, active patients but carry a risk of high metal ion levels, a consequence that is poorly understood.

Ceramics, especially alumina-alumina combinations, have produced excellent rates of survivorship. Although the rate of catastrophic fracture has declined, caution should be advised with regard to the patient's lifestyle activities and body mass index. Studies of conventional zirconia show inconsistent results, possibly as a result of manufacturers' variability and phase transformation with time.

It is too early to comment on the performance of Oxinium, although ongoing work will prove whether or not it fulfills its early promise.

Although ceramics seem to be the future, they are more expensive which, combined with the small but significant

**Table 2. Friction coefficients of different bearing couples**

Bearing couple	Coefficient of friction (µ)
Native joint	0.002
Alumina–alumina	0.05
Alumina–ultra-high molecular weight polyethylene	0.05
Zirconia–ultra-high molecular weight polyethylene	0.06
Cobalt-chrome–ultra-high molecular weight polyethylene	0.08
Cobalt-chrome–cobalt-chrome	0.12

risks of fracture, still makes metal-on-highly crosslinked polyethylene an attractive choice. Allying patient factors with a sound knowledge of the tribology of the hip will allow the surgeon to choose the prosthesis best suited to the patient. **BJHM**

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## KEY POINTS

- The choice of materials used to make a bearing couple is a key decision in total hip replacement.
- Metal, polyethylene and ceramic are most commonly used for articulation.
- Metal is very hard and tough but generation of metal particulate matter and ions is a concern with metal-on-metal articulations.
- Ceramic is also very hard and generates less wear debris but carries a risk of component fracture.
- Polyethylene is the most common material used for acetabular articulation since it does not carry a risk of fracture or risk of systemic complications. However, it is prone to wear debris generation which can lead to premature loosening and bone loss.