Review Article

A critical appraisal of the evidence regarding the choice of common bearing couples available for total hip arthroplasty

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Abstract

There are a variety of materials used in bearing components in total hip replacement (THR). Metal-on-polyethylene replacements, having undergone small technical refinements in design over the last 30- 40 years, give, according to the Scandinavian hip register, very good 10-year outcomes. However, aseptic loosening, caused to a great extent by adverse biological local reactions, induced by wear products from the articular surfaces, remains a serious problem. Thus, the debate and challenge of finding the best bearing surfaces continues. Technical improvements have been advocated in recent times to improve the replacement bearing longevity. Other than discussing such improvement, the paper looks at the evidence surrounding materials that are commonly used in total hip arthroplasty. This has been done to empower surgeons to make more informed decisions when choosing the bearing surfaces for their patients.

Keywords: Total hip replacement, Articular surfaces, Arthroplasty.

Introduction

Currently there are a wide variety of materials used in bearing components in total hip replacement (THR). One might think that it would be easy to develop the ideal bearing surfaces for hip replacement. Decide what characteristics you want the bearings to have and then select the materials which will provide these characteristics. It is not that simple though. Charnley realised the difficulty of this problem with the failure of his first teflon acetabular components. It was only through these failures that he developed his much successful "low friction hip" which was the first successful metal-on-polyethylene THR. Not to be outdone, surgeons have been following suit by learning from their failures in developing alternative bearing surfaces ever since. It seems that success is not uncommonly born out of failure.

Low-friction and low-wear were obvious desirable characteristics for the articulating THR surfaces. In addition, implant materials also had to withstand the corrosive environment of the body and its fluids. Up till now the traditional metal-on-polyethylene THRs have only undergone small technical refinements in design over the last 30-40 years. Yet they give, according to the Scandinavian hip register, very good (more than 90%) 10-year survival outcomes. However, aseptic loosening, caused to a great extent by adverse biological local reactions, induced by wear products, remains a serious problem. There are four modes of wear which contribute to wear products. The most significant mode is between the primary bearing surfaces on each other. Thus, the debate and challenge of finding the best bearing surface continues. Different types of technical improvements have been advocated in recent times to improve the THR bearing longevity. The differences in age, weight and function demand of patients have helped drive the development of so many different types of bearing surfaces on the market. This paper endeavours to discuss these different types of articulations in order to critically analyse the evidence regarding the common and popular bearing surfaces used in hip arthroplasty today. It also focuses on ultrahigh molecular weight polyethylene (UHMWPE), the newer highly crosslinked UHMWPE cups, ceramic-on-ceramic and metal-on-metal articulations.

Highly cross-linked UHMWPE:

It has been found that polyethylene (PE) debris generated by adhesive/abrasive wear cause a tissue reaction. This 'tissue reaction' leads to periprosthetic osteolysis component loosening and failure. This osteolysis has become one of the most notable factors affecting long-term survivorship of the total hip arthroplasty (THA).[1] Therefore, alternative bearing surfaces have been suggested to reduce this problem but have other disadvantages.[2]

As with many innovations, highly crosslinked PE was discovered by chance. It was noticed that THR with polyethylene cups that had been sterilised by being irradiated with gamma radiation had a better longevity. In fact, wear seemed to be reduced and radiographs showed less signs of osteolysis or loosening.

Gamma radiation was later found to cause cross-linking of the UHMWPE cups. This in turn has been reported to markedly improve its wear-resistance. This has been proven both in vivo[3] and in vitro.[4,5] The resultant increase in longevity of hard-on-soft polyethylene cups is due to a reduction in wear and debris associated osteolysis.

Long-term retrospective radiographic studies have also shown significantly improved wear resistance in vivo in acetabular components made from these strongly cross-linked polyethylenes.

Wroblewski reported on wear rates of silane cross-linked polyethylene. After an initial bedding-in period of penetration of 0.2-0.4mm/year, which was presumably "creep," the subsequent average penetration decreased to 0.02mm/year, representing the true wear rate. Therefore UHMWPE dramatically reduces wear rate regardless of the method used to induce cross-linking.[3]

Cross-linking can be achieved by generating free radicals along the backbone of long chains which make up the polyethylene molecules. The free radicals in adjacent chains combine with each other by forming carbon-carbon covalent bonds, which are the so-called cross-links. The free radicals can be generated in a number of ways. These include exposing the chains to ionising radiation, peroxide or silane substances.[3]

Although most free radical chains formed covalent bonds with each other, some were left unbonded. This would allow for oxidation of these chains and cause the polyethylene to become brittle. Therefore, more contemporary manufacturing of highly cross-linked UHMWPE involves using ionising radiation (either gamma or E beam) to induce cross-linking, followed by further treatment (either with heat or vitamin E) to release trapped free radical chains allowing them to form further covalent bonds with each other.

These contemporary methods of manufacturing UHMWPE have been shown in hip simulator studies[4,5] to markedly improve wear resistance. Muratoglu found that electron beam cross-linked UHMWPE liners showed no detectable (penetration) change indicating excellent wear resistance. Also that the wear resistance was independent of femoral head size (22mm to 46mm).[6]

Early clinical results seemed not to be as fruitful as simulator studies in demonstrating reduction in the wear rates.

This was due to two reasons. Firstly, some studies compared highly cross-linked polyethylene cups with a standard cup sterilised with gamma radiation. This gamma sterilisation results in cross-linking itself and a reduction in wear rates depending on the amount of radiation used (50% with 25kGy and 75% with 40kGy). Therefore, detectable wear differences were smaller. Secondly, even when a gas-sterilised cup was used as control, detectable differences in penetration were minimal. It appeared that both highly cross-linked and standard polyethylene cups had a much higher initial rate of wear in the first few years before this settled down. This has since been explained as creep and not true wear. This initial period, termed the 'bedding-in' period, does not accurately reflect true wear from penetration measurement and it is only now that we are getting data from mid-term trials that we are finding the true wear reduction value of using UHMWPE.[7,8]

Dorr et al. found the wear rate of 37 Durasul acetabular liners (cross-linked with 95kGy, was on average 55% lower than a standard (gamma-sterilised 25-40kGy) at five years post-operatively.[8]

D'Antonio et al. found a 60% wear rate reduction at 4.9 years when comparing 56 crossfire liners (105kGy cross-linked) to a standard gamma-sterilised cup (25kGy sterilized). He also stated that there were fewer osteolytic lesions and no revisions in the crossfire group.[9]

Engh et al. likewise found a 95% lower wear rate in 76 Marathon liners (50kGy cross-linked) at 4.1 to 7.2 year follow-up compared to a gas plasma-sterilised control.[10] The high reduction in wear rate here compared with those stated by Dorr and D'Antonio is likely to be due to the control that Engh used which was not sterilised with gamma radiation and therefore not cross-linked at all.[7,9]

The relationship between wear rate and osteolysis has been well documented for traditional polyethylene liners. Thus far, only one case report has been published of clinically relevant osteolysis in a total hip replacement with a highly cross-linked polyethylene liner. This seems to show promise that we have made good progress in genuinely increasing the lifetime of THA using hard-on-soft or metal on UHMWPE bearings.

This reduction in wear rate seems to be evident whether one is using a metal or alumina ceramic head. Wroblewski et al. published 10-year follow-up results of an alumina ceramic head and UHMWPE articulation. Mean penetration at 10 to 11 years 3 months was 0.37mm, giving a mean rate of 0.037 mm/year. The authors pointed out that a similar study had used stainless steel with a UHMWPE articulation and found a mean penetration of 0.11mm/year. Thus although the use of UHMWPE as the liner reduces penetration so does the head material.[3,7]

Finally, the latest papers seem to be on focusing on the different methods of extinguishing the remaining free radicals after initial cross-linking. Some are using three sessions of gamma dosing, or heat treatment, while others are using vitamin E. These further treated UHMWPE liners have yet to bear trials with mid or long-term results to suggest that one is better than another.[7]

Ceramics:

Ceramics are non-metallic and inorganic material.[11] The usual processing of ceramic consists of mixing the powder together with water and adding an organic binder. The mixture is then pressed into a mould to obtain the desired shape. Subsequently it is dried to evaporate the water and the binder is burned out by thermal treatment. The final microstructure of the ceramic is greatly dependent on the quality and purity of the initial powder, and on the control and precision of the thermal process applied. Alumina is one form of ceramic used in arthroplasty. It has a Young's modulus of 300 times that of cancellous bone, and 190 times higher than polymethyl methacrylate (PMMA). Alumina ceramics have excellent compressive strength and have a linear elastic behaviour. Alumina is monophasic, polycrystalline, very hard, very stable, and highly oxidised with a high thermal conductivity coefficient, low bending stress and low resilience. The resulting material is in its highest state of oxidation, allowing thermodynamic stability, chemical inertness, and therefore excellent resistance to corrosion. The ionic structure of alumina ceramic creates a hydrophilic structure and fluid film lubrication, resulting in higher wettability than that of orthopaedic polymers and metals. It has been shown in vitro that water is absorbed with high bond strength and proteins quickly and completely cover the ceramic surface with a monolayer after surgical implantation. This phenomenon improves lubrication of the joint.[12,13]

Zirconia ceramic is a very different material. It was introduced in an attempt to overcome some of the shortcomings of alumina ceramic. However, it had several shortcomings of its own. This material was unstable, existing in three phases: monoclinic, tetragonal and cubic. Phase changes resulted in large volume changes and decreased mechanical properties of the material because of crack production. Yttrium has been used to stabilise zirconia ceramic in its tetragonal phase. However, despite this there was still a tendency for it to change phases to the monoclinic phase with time. This ceramic has been for now fallen out of favour in its pure form due to these difficulties, but is still being looked at when combined with alumina.[13]

Alumina-on-Alumina:

If the aim is to improve the longevity of the THA, and we know that alumina on UHMWPE provides less wear than conventional alloys on UHMWPE, then why not alumina-on-alumina? Before the advent of UHMWPE ceramic alumina on alumina has been used for just this reason.

The alumina/alumina combination was first used by Boutin in 1972[14] and later by Mittlemeier in Germany, Furuya in Japan, Pizziferato in Italy and Salzer in Austria. Their aim was to reduced debris associated osteolysis already described by Willert et al. by replacing the articulating components with more durable ones.[14] Due to initial reports of fracture risk, early failure and osteolysis, the uptake of this articulation was mainly in Europe.[15] Evolution of this material over time has yielded better results and this has led to the spread of its popularity worldwide.[16]

From its introduction period in the 1970s, the ceramic was relatively low-density, had a high porosity and was manufactured from large granules (up to tenths of microns).[17] Modern alumina has mean grain sizes of 2.2 ± 1µm, obtained from improved manufacturing. Further improvements in micro and macrogeometry (smoothness and sphericity) have also been made. Clearance of the two components has been shown to be optimal at 50µm and when combined with the manufacturing improvements have resulted in greater implant longevity.

Concerns of ceramic fracture seemed to have reduced with the improvement of ceramic quality and rests at approximately 1 per 2000 for a ten-year period. This was an improvement from 1% obtained with the older ceramic components.[18,19]

Retrieved implant studies initially demonstrated a linear wear of 5-9µm/year with well-placed components.[17] Again implant quality has been shown to have a direct relationship on wear.[20] Prudhommeaux also calculated that the overall wear, calculated by the weight of debris generated, was in the order of 1000 times less than metal-on-standard polyethylene and 40 times less than metal-on-metal articulation.[20] The wear rate of modern, well-manufactured ceramic-on-ceramic components is in the order of 3 µm per year, but can be more than ten times this if implants are mal-positioned.[16]

Due to the reduced wear rates with alumina-on-alumina components, loosening has been put down to mechanical factors, alumina rigidity or poor cementing techniques. This hard material has lead to concerns that the less adaptable ostoeoporotic bone cannot adapt to it and fracture. Hence it has been more commonly used in the young (Wolff's Law). Bizot et al. found aseptic loosening of the cemented socket significantly more frequent in the older compared with the younger population and also with larger socket sizes.[16,21] We actually switched to using a polyethylene socket with ceramic or metallic head in this group of more elderly patients for this reason. Elastic mismatch between bone and alumina ceramic or between bone and polymethylmethacrylate would be more pronounced in ostoeoporotic elderly patients.

Osteolysis has still been described in the literature for this articulation. However, it appears, as with other articulations, that abnormal contact of components which occurs with poor positioning increases this risk.[22] The majority of the evidence from long-term trials, however, seem to agree that there is a very low rate of osteolysis with ceramic-on-ceramic articulations.[23]

Several in vitro studies have shown alumina-on-alumina to be one of the best friction couples available.[24,25] Comparative studies of alumina-on-alumina versus metal-on-PE favoured the ceramic couple. The outstanding tribologic properties of the alumina couple are related to a low surface roughness (Ra=0.02µm) because of low grain size, a high wettability, a high hardness (giving good scratch resistance) and fluid-film lubrication. In vivo wear has been calculated to be less than 0.01mm^3 per million cycles after the first run-in phase of one million cycles, where it is 0.1-0.2 mm^3 per million cycles. These results have been confirmed by Clarke for up to 14 million cycles.[25] These figures are about 2000 to 5000 times less than that of metal-on-PE friction couple. The friction coefficient of the alumina couple is 0.9 versus 0.21 for metal-on-PE bearings.[13] Some studies have, however, shown in vivo wear to be more than in vitro wear results. So that the wear that occurs in real life may not be as dramatically reduced.

Contrary to metal-on-PE articulations, the alumina-on-alumina combination does not favour a small head size. Also alumina femoral heads ranging from 32-36mm generate little debris as the bigger heads draw in more fluid for lubrication.[26]

Once the risk of fracture had been dramatically decreased to an acceptable level, it became obvious that the weak link was the long-term fixation of the acetabular component. It sometimes loosened and needed subsequent revision. Many methods of acetabular fixation have been tried, including the use of cement, press fit bulk alumina cups, and screwed in Titanium (Ti) shells. Finally, hydroxyapatite (HA) coated Ti shells with alumina modular inserts are being used which have published cup survival of 85% at 15 and 20 year follow up.[12]

Alumina-on-PE:

Because of the relatively low survivorship of the acetabular component in alumina-on-alumina, some reverted back to the gold standard of PE for the cup, but retained the ceramic head. Sugano published his findings of 57 THA in patients with a mean follow-up of 11.1 years. He reported radiological loosening in 3 femoral components and 16 ceramic acetabular components. Wear of the socket was 0.1mm per year. Comparable results have also been published elsewhere.[27]

Studies have compared alumina and metal heads directly. One such study used the same head size and found that the revision rate at 10-year follow-up was 30% less in the alumina-on-PE group. Wear rate after the initial bedding-in period was 0.1mm/year for ceramic heads compared to 0.2mm per year for metal heads.[28]

Long-term results have been published to support the use of this articulation. Le Mouel et al has reported a 93% 10-year survival of 156 alumina-on-PE THA and Urban et al reported on 64 alumina-on-PE cases. The mean linear wear rate was 0.034mm per year with a survival of 79% with 20 year follow-up.[29]

Metal-on-metal Bearings:

In the early 1960s, metal-on-metal THRs were relatively common. They were gradually phased out by the mid-1970s in favour of metal-on-polyethylene bearings. This was mainly due to their higher loosening rates and concerns of biological reaction to the alloy constituents. Again concerns over osteolysis were thought to originate from polyethylene wear debris from metal-on-polyethylene articulations that led to the revival of metal-on-metal by the late 1980s and its popularity seems to be increasing.[30]

The first generation metal-on-metal THA, which included the McKee-Farrar, Mueller-Huggler and Sivash total hip replacements, were quite crude in design. There were very few long-term published results concerning them, but studies noted their high revision rate due to component loosening. One such study published a follow-up of 13-14 years, with a survival rate of 84.75%. However, about 50% of the follow-ups at this point showed radiological loosening in the stem and the cup.[31]

A comparative study between McKee-Farrar and Charnley prostheses showed comparable 20-year survival. Again it was noted that older patients in the study were more likely to have component loosening in the McKee-Farrar group. Other studies published metal-inducing tissue reaction, and this was attributed to the high rate of osteolysis noted at retrieval.[31] Evidence from papers such as these converted many surgeons to using metal-on-polyethylene and abandon metal-on-metal. This was despite the fact that wear rates from retrieval studies for these prostheses had shown very low wear rates.[30,31]

In the 1980s, better finished metal-on-metal components started to be used again, resulting from encouraging data from hip simulator studies.[30,32] Again wear rate was noted to be good. In fact they were better than the first-generation m/m articulations, but loosening remained an issue. Some studies stated revision rates as high as 70% although this was for loosening and dislocation combined. In addition, metal ion release became more of a concern resulting in studies measuring their concentration in serum, blood and urine.[33] Despite low wear rates, the metal ion levels were many times that in control groups. These metallic wear particles have been shown to elicit an osteolytic response, but have also been found in para-aortic lymph nodes, the liver and the spleen. Granulomas in liver and spleen have also been found as a result of high concentrations of metal ions.[34]

Besides, an increased (almost double) dermal hypersensitivity to metal ions have been found in patients with these THR compared with metal-on-polyethylene THR,[30] although it is unclear if this affects the prosthesis longevity. More worrying is the 250% and 350% increase in aneuploidy and chromosomal translocation found in peripheral blood lymphocytes in patients with metal-on-metal articulation THAs.[35] One may assume that the biological risk of that from metal-on-polyethylene, ceramic-on-polyethylene or ceramic-on-ceramic bearings would be lower as less debris would be formed. However, again a higher rate of cancer development has not been proven in any study to date and long term risk of using the metal-on-metal bearings is not known.

Conclusion

The principal implications of the developments in all of these bearing surfaces in recent years are two-fold. Firstly, reduced wear has reduced debris causing osteolysis and aseptic loosening and, thus, increased the longevity of the THR. Secondly, in the case of UHMWPE, thinner sockets may possibly be used in the future to accommodate larger head sizes. This would have the added advantages of reduced incidence of dislocation, a greater range of movement, and less impingement on the femoral neck.

Patients have different requirements from their THR implants depending on their age, gender and lifestyle and as long as there is this diversity, there will be a host of different implants made with different materials to cater to them. It is not possible to say that one bearing combination is better than the rest, but one must endeavour to tailor the selection of bearing surface to the patient to ensure satisfaction and the longest possible implant life. However, better quality and more refined implants have resulted in most of the common bearing combinations mentioned in this paper having improved wear rates.

What has been proven is that no matter which materials are being used in the THA, correct implantation techniques and alignment of components is the most important factor in avoiding early failure.

While focussing on the common bearing surfaces used in THAs, this paper does not extrapolate on different ways of fixing them to the femur or acetabulum or problems which might be encountered with patients with poor acetabular bone stock. It also does not explore the concept of resurfacing or other bone preserving techniques of surgery. Other important concepts such as the size of femoral head and its effect on joint stability and range of motion have also not been covered here as they are outside the scope of this paper. While discussing wear characteristics of different bearing couples, it has not elaborated on the effect of implant position as a reason for increased wear because this is independent to the bearing couples and applies to all bearing surfaces.

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