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Bearing surfaces in primary total hip arthroplasty

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■ Total hip arthroplasty (THA) is widely considered one of the most successful surgical procedures in orthopaedics. It is associated with high satisfaction rates and significant improvements in quality of life following surgery. On the other hand, the main cause of late revision is osteolysis and wear, often a result of failure of bearing surfaces.

■ Currently, several options are available to the surgeon when choosing the bearing surface in THA (ceramic-on-ceramic (CoC), ceramic-on-polyethylene (CoPE), metal-on-polyethylene (MoPE)), each with advantages and drawbacks.

■ Very few studies have directly compared the various combinations of bearings at long-term follow-up. Randomized controlled trials show similar short- to mid-term survivorship among the best performing bearing surfaces (CoC, CoXLPE and MoXLPE). Selection of the bearing surface is often 'experience-based' rather than 'evidence-based'.

■ The aim of this paper is therefore to evaluate the main advantages and drawbacks of various types of tribology in THA, while providing practical suggestions for the surgeon on the most suitable bearing surface option for each patient.

Introduction

Total hip arthroplasty (THA) is widely considered to be one of the most successful surgical procedures in orthopaedics. It is associated with high satisfaction rates and significant improvement in quality of life following surgery.[1,2] According to recently published data from the British National Joint Registry, the cumulative survival of THA at 13 years is 93.2%, with 80% of implants surviving up to 20 years.[3,4] Moreover, the number of THAs performed worldwide is increasing. According to the Australian Arthroplasty Registry, there was an increase of 5.5%

between 2015 and 2016, and an increase of 109.7% between 2003 and 2016 in that country.[5] In Italy, between 2001 and 2015, there was an annual increase rate of 2.5% for THA performed.[6]

While THA is a successful procedure in most cases, failures are still recorded. Overall, excluding metal-on-metal (MoM) bearings from the analysis, failures due to articulating materials represent around 5% of the total number of implants.[3,5] When considering only late failures, defined as the ones occurring after ten years or more, osteolysis and implant wear become the most common causes for revision when associated with aseptic loosening.[7,8]

The pathophysiological mechanisms of polyethylene wear-induced osteolysis have been extensively studied.[9-12] It has been shown that debris particles can induce a cellular response in periprosthetic tissues, with the up-regulation of toll-like receptors (TLRs) on macrophages. TLR signaling leads to up-regulation of many chemokines and cytokines, such as TNF-α, IL-1β, MCP1 and others. The inflammatory response that ensues leads to the activation of osteoclasts and induction of local bone resorption.

Currently, several options are available to the surgeon when choosing the bearing surface in THA (Table 1). The most common material for acetabular liners is polyethylene (PE), either ultra-high molecular weight PE (UHMWPE) (the so-called 'standard' or 'conventional' PE) or cross-linked UHMWPE (XLPE), or ceramics or metal; the latter nowadays abandoned and withdrawn from the market for THA.[13] Heads can be made of ceramics or metal alloys, usually CoCr (Cobalt-Chromium).[14] Thus, there are several combinations of liners and heads that can be selected, each one with its own well-known advantages, but also disadvantages (Table 1).[15] Wear and osteolysis are described as occurring mainly with conventional PE bearings associated with metal or ceramic heads (MoPE or CoPE). XLPE has been reported with less wear (MoXLPE or CoXLPE), but also with a decrease in mechanical properties; ceramic-on-ceramic (CoC) is related to much less wear and the highest bio-tolerability but carries the risk of breakage and noise from the implant following arthroplasty. Very few studies have directly compared the

Table 1. Main disadvantages for each bearing surface

Couplings	Main disadvantage
Metal-on-polyethelene	Wear and osteolysis
Ceramic-on-polyethelene	Wear and osteolysis
Metal-on-XLPE	Decreased mechanical properties
Ceramic-on-XLPE	Decreased mechanical properties
Ceramic-on-ceramic	Breakage and squeaking
Metal-on-metal	ARMD (ALVAL, high ion levels, osteolysis, pseudotumours)

Notes: XLPE, highly cross-linked polyethylene; ARMD, adverse reaction to metal debris; ALVAL, aseptic lymphocyte-dominant, vasculitis-associated lesion

various combinations of bearings at long-term follow-up. Randomized controlled trials (RCTs) show similar short- to mid-term survivorship among CoC, CoXLPE and MoXLPE in patients younger than 65 years.[16] Thus, clinical decisions on the choice of the bearing are still based on very limited evidence.[17]

This approach is reflected by trends and usage percentages of bearing surfaces in major geographical areas: in the United States the use of ceramic heads increased between 2012 and 2016, while the use of metal heads decreased (60% metal and 36.8% ceramic in 2012, to 42.6% metal and 52.8% ceramic in 2016).[18] In Italy, the only available data refer to a single region, Emilia-Romagna: between 2001 and 2013 a steep increase in CoC coupling was observed (20.5% compared with 62.1%), associated with a decrease in metal head usage (41.2% to 10.3%).[19] Conversely, in the United Kingdom, since the decline in usage of MoM bearings in 2010, an increase in CoP has been observed (12.2% in 2010 to 32.7% in 2016; data refer to uncemented prostheses), with a decrease in CoC (39.5% to 24.9%), while MoP couplings remained constant.[3] These data highlight a substantial difference in trends and overall percentage of selection of various bearings.

In this paper, a brief review of the main advantages and drawbacks of various types of tribology in THA will be discussed, while providing practical suggestions for the surgeon on the most acceptable bearing surface option for each patient, based also on the extensive personal experience of the authors.

Some definitions

It is helpful at this point to consider and to clarify some definitions when considering bearings.

Tribology

The science that studies friction, lubrication and wear between two surfaces which are in close contact and move one on the other. The name is derived from the Greek word 'Τριβος,' which means rubbing.

Wear

The surface damage with progressive loss of material (debris) due to friction between moving surfaces.

Debris

Particles of different material and size shed from the surface of the various parts of the implant due to wear.

Fretting

Relative low amplitude movement (oscillation and sliding) between two mechanically joined parts, under load conditions (between 1 μm and 100 μm). All modular junctions are susceptible to the loading of the body. It provokes wear (debris) and corrosion.

Corrosion

Surface degradation due to electrochemical interactions producing metallic ions and salts which applies only to metals. Different distinct forms of corrosion have been described (galvanic, fretting, crevice, stress, etc).[20]

Osteolysis

Bone resorption due to biological response to debris including osteoclast activation that can compromise the bone stock around the implant and lead to loosening of the prosthesis in the advanced phase.

Conventional and cross-linked polyethylene

Conventional and cross-linked polyethylene PE liners are the most common choice in THA. UHMWPE was introduced in the early 1960s by Charnley, and was widely used until the last decade, when it has been progressively replaced by XLPE.

When considering PE liners, not only the material, but also the type of sterilization is of major importance for the mechanical properties and for the biological effects. Until the mid-1990s, the most common sterilization method for UHMWPE was gamma irradiation. Whilst this method increases cross-linking between PE molecules, generating a more wear-resistant material, when performed in presence of oxygen, it also produces free radicals. Free radical oxidation makes PE more brittle, with reduced resistance and increased wear. Several studies highlighted how the use of a different sterilization method improves PE wear resistance.[21-23] Thermal sterilization with gas plasma has been shown to improve wear and oxidation resistance *in vitro* when compared with gamma irradiation in the presence of oxygen. On the other hand, sterilization with gamma irradiation in an air-free environment and oxygen-free packaging could theoretically reduce the risk of free radical oxidation, while maintaining the increased cross-linking

between PE molecules. In a ten-year follow-up study by Engh et al,[24] PE liners sterilized by oxygen-free gamma irradiation showed less head penetration and less osteolysis when compared with both gas plasma and gamma irradiation in air. Thus, when choosing or revising a PE liner, a knowledge of the sterilization method is necessary. Oxygen-free packaging in gamma-irradiated PE should be the preferred method, together with PE sterilized in ethylene oxide; currently these show good clinical long-term results and are preferred by many sterilization stakeholders.

In the last 15 years, conventional PE liners have been progressively abandoned in favour of XLPE liners. Currently, XLPE is used in the 98% of THAs in which a PE liner is selected.[5] XLPE is defined as UHMWPE that has been irradiated with at least 50 kGy of gamma (or beta) or electron beam radiation. This treatment induces the crosslinking between PE molecules, with the rationale of increasing wear resistance. In the last few years the first long-term follow-up studies have been published, and reduced wear, together with a better survival of XLPE when compared with standard PE were found.[25,26] The better long-term results with XLPE were confirmed by registry data in the 2017 Australian Registry report. The rate of revision at 16 years for XLPE was 6.2%, compared with 11.7% for non-XLPE.[5] It is worth noting that a recent study found an increase in wear rate in XLPE compared with standard PE starting from the tenth year of follow-up, thus raising a first concern on the very long-term performance of XLPE.[27]

The surgeon must keep in mind that not all XLPEs are the same, considering that aside from irradiation, melting technique and annealing can also influence the *in vivo* proprieties of XLPE. XLPE liners annealed after irradiation and below the melting temperature usually show good wear and fatigue performances but poor oxidation resistance; this happens because this process fails to neutralize all free radicals. On the other hand, XLPE liners re-melted after irradiation show good oxidation resistance but less fatigue resistance.[28]

The cross-linking process, while increasing the wear properties of PE decreases the mechanical ones, making the liners more at risk of fatigue fracture. The irradiation of PE generates free radicals that can react with oxygen and could compromise the mechanical properties over time.[29] As a matter of fact, breakage of XLPE liners has been widely described in particular when old types of locking mechanism and designs were used.[30,31] Moreover, steep positioning of the acetabular component which leads to stresses concentration or impingement is considered a risk factor.[32]

Recently, XLPE liners with the addition of antioxidants such as Vitamin E were introduced into the market with the aim of reducing the oxidation *in vivo*. The Vitamin E can be mixed in PE powder or added through diffusion after machining. The rationale for Vitamin E addition is to act as an antioxidant reacting with the free radicals that remain instead of oxygen.[33] In this way, re-melting is not necessary to avoid the oxidation, and mechanical properties are saved. As a consequence, the liner can also be thinner and larger heads can be used, with a possible improvement in joint stability. While the early clinical results are promising, with a low wear rate reported even with 36-mm diameter heads, the follow-up is still too short to evaluate potential clinical advantages over regular XLPE liners[34-36] and registry data show no difference between XLPE and Vitamin E XLPE.[5]

Because of the influence that the discussed elements have on *in vivo* performance of the PE liners, the surgeon must be aware of the chosen liner characteristics concerning sterilization and production processes, in order to choose the optimal one for each patient.

Two other main factors need to be considered when evaluating the long-term performance of a PE liner: the diameter and the material of the femoral head. Larger diameter heads are associated with increased wear and revision rate for osteolysis when coupled with standard PE.[5,37] Interestingly, no increase in XLPE wear rate with the use of larger diameter heads (> 32 mm) was reported.[38] Moreover, good results with XLPE at a medium-term follow-up were reported even with the use of large diameter ceramic heads.[39] These observations were recently confirmed by registry data that reported a ten-year survival of 95.3% of THA with XLPE and a femoral head > 32 mm.[5] These data could allow surgeons to use larger femoral heads even when selecting a XLPE liner, but in standard routine cases no more than 36 mm is suggested according to the acetabular component size for safety reasons, as there is a lack of information for head sizes larger than 36 mm. The thickness of XLPE should provide enough fatigue resistance to the components. For this purpose, the design must also be considered. In our experience, we use larger femoral heads when we can select a XLPE liner with a minimum thickness of 6 mm, that means in acetabular components with a minimum size of 56 mm[40] (Fig. 1).

Concerning the choice of femoral head, few data are available, with only small series and at short follow-up intervals[41,42] and no long-term follow-up RCTs directly comparing metal *versus* ceramic heads coupled with XLPE.[16] In a recent study by Cafri et al,[37] based on a systematic analysis of registry data, an overall equal long-term performance was found between metal and ceramic heads. Data from the Australian registry suggested a lower revision rate of CoXLPE when compared with MoXLPE.[5] Theoretical advantages of the ceramic compared with the metal heads are: the higher hardness with less risk of damage during implantation, the surface finishing with only negative peaks due to grains detachment rather than deformation, and the higher wettability thus producing a
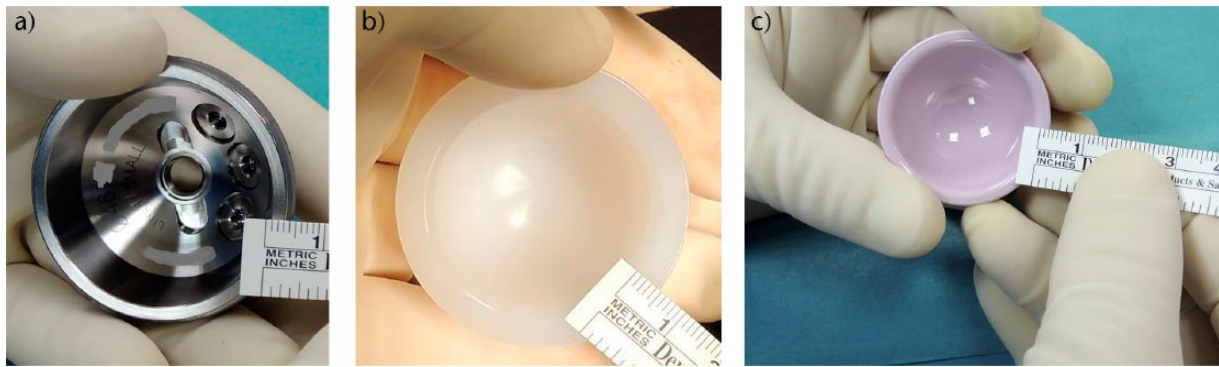
Fig. 1 Intra-operative measurement of acetabular components and liner of a total hip arthroplasty: a) the metal back has a minimum thickness that must be taken into account; b) a minimum polyethylene (PE) thickness must be preserved even when selecting large diameter femoral heads; c) ceramic liners can be thinner than PE liners.

better lubrication of ceramic which can lead to less friction and scratching and theoretically less liner wear.[43] Moreover, alumina does not induce biological intolerance and it is considered to be the material with the best biocompatibility. On the other hand, several recent studies reported the occurrence of adverse local tissue reactions to metal debris with the use of a metal head coupled with PE liners, due to trunnionosis at the head/neck junction.[44-48] Patients developed soft-tissue damage, pseudotumours, osteolysis and had higher blood metal ions levels. This occurrence is due to fretting at the taper/head junction, and was reported with implants of different manufacturers. In a retrieval study by Kurtz et al,[49] the fretting and corrosion at the taper/head junction were evaluated either with ceramic and metal heads. Ceramic heads showed significantly less fretting and corrosion, independent of the stem alloy used for the testing. Trunnionosis at the metal head-neck junction is a possible cause of painful THA that needs to be excluded after ruling out other causes of failure such as infection, but at the moment the feeling is that it could be a somewhat overestimated event. No one knows the real incidence of this phenomenon on a large scale and further research is needed.

Two potential limitations to the use of ceramic heads are worth discussing: the risk of fractures and the increased costs. While a detailed explanation of ceramic fracture mechanisms is given below, it must be noted that the risk of head fracture is lower than the risk of liner fracture and is reported as occasional and insignificant in combination with PE.[50] A clean engagement of the head in the stem taper is required to reduce fracture risk. Concerning the costs, ceramic heads are more expensive than metal heads. However, in a model that accounted for the increased risk of trunnionosis with metal heads, the routine use of ceramic heads has showed comparable cost-effectiveness to metal heads.[51] No population-based studies have estimated the real-life cost-effectiveness of routine ceramic

head use. With the increasing use of ceramic heads, we can expect that the price will decrease and, at the same price as metal heads, there should be no objections to the claim that CoXLPE could be preferable to MoXLPE.[2]

Ceramicized metal (Oxynium)/XLPE is the bearing surface with the highest survival at ten years in the Australian Registry,[5] but the Registry report advice is to interpret this result with caution. The reason is that this is a single company product, used with a small number of cases. This may have a confounding effect on the outcome, compared with the other bearing surfaces used in many different combinations.

In our clinical practice, XLPE liners with ceramic heads are the first option in older patients, or in younger patients when a reliable correct positioning of the acetabular component cannot be obtained intra-operatively due to anatomical abnormalities.

Ceramic on ceramic

The other option among the best performing bearing surfaces is CoC. The first ceramic acetabular components were introduced in the 1970s by Pierre Boutin in France as cemented liners and in 1974 by Heinz Mittelmeier in Germany as cementless threaded liners and skirted heads. However, this generation of ceramics was characterized by a high rate of aseptic loosening and failure due to the poor fixation of both cemented and cementless implants, inadequate designs such as the bulky skirted heads and the strength problems due to the grain size of the first generation of alumina. Modern ceramic acetabular components featured titanium shells with rough surface finishing in which a ceramic liner is located while in the 1990s the alumina further improved to a higher purity grade with more uniform and smaller grains. This type of implant has a large number of long-term follow-up studies, with good to excellent clinical results.[52-54]

Nowadays the most commonly used ceramic is the alumina matrix composite (AMC) (Biolox Delta; CeramTech AG, Plochingen, Germany). In 2016, AMC accounted for 92.0% of all procedures with CoC bearing surface in the Australian Registry.[5] AMC, introduced in the early 2000s, is the fourth generation of Biolox Ceramics, composed of 82% alumina and 17% zirconia, with the addition of chromium oxide (0.5%) to enhance hardness and strontium crystals (0.5%) to diffuse crack energy. This material has a smaller grain size (< 0.8 µm) compared with previous ceramics, and was developed in order to reduce the risk of implant fractures. In the last few years mid- to long-term follow-up studies of AMC have been published, with a ten-year survival rate from 98% to 99.3% at two to ten years.[55] These excellent results are confirmed by registry data: the Australian Registry reports a CoC survival of 92.8% at 15 years.[5]

When compared with XLPE, CoC bearings have some advantages worth noting. The first advantage is the very low friction and very low wear rates. This is due to the hardness and high wettability of the surface, as mentioned above, of the ceramic heads. Moreover, the few wear particles generated by ceramic components induce a less intense biological reaction compared with polyethylene debris. Histological analysis of long-term retrievals indeed found wear debris in individual macrophages, but the inertness of such debris does not trigger the granulomatous reaction necessary to induce osteolysis. A second advantage of CoC bearings is that wear is not directly dependent on the head diameter. This allows the surgeon to select a larger diameter head with fewer concerns compared with PE liners. The AMC liner can also be thinner (3 mm to 4 mm) compared with XLPE ones. Registry data[3] show that when using a CoC coupling, larger diameter heads (36 mm) have significantly better survival rates at 14-year follow-up when compared with smaller heads (32 mm), while 28 mm heads have the highest revision rate, mainly in the first years after surgery. The 40 mm heads have a good survival, similar to 36 mm, but the follow-up is still too short, suggesting that these results should be interpreted with caution. These observations could be explained by a reduced risk of dislocation with the use of larger heads.

CoC bearings have some drawbacks that limit their widespread use. The first limitation of ceramics is the brittleness of the material that increases the risk of fracture. Ceramic fracture is indeed a catastrophic complication that can occur with the use of such material. With modern ceramics, studies report only occasional occurrence of fracture of the head, with higher risk of occurrence in the short neck 28-mm head.[56] Liner fracture has been reported with a higher frequency, with percentages between 0.13% to 1.1%, with differences among metal-backed brands.[57,58] Liner fractures are almost never related to direct trauma, but rather depend on three main mechanisms: misalignment during insertion of the liner, metal back damage or acetabular component malposition that leads to impingement and edge-loading. Excessive anteversion ($> 25°$) has been demonstrated as the main clinical risk factor for liner fracture due to impingement.[59]

Correct positioning and handling of the components is very sensitive in the case of CoC, which has a very low wear bearing surface, but is less forgiving. Also, metal back deformation[60] during the insertion is critical as titanium shell can deform during impaction, consequently generating a two-point support of the liner to which ceramics are vulnerable.[61] Thus, careful preparation of the acetabulum and assessment with a trial insert is required when using a ceramic liner. Not all the metal backs are the same in terms of thickness, stiffness and tools for implantation. A small change can cause a big difference during engagement of the taper of the ceramic liner in the shell. This could be due to a flawed design of the components or to a surgical fault. Again, intra-operatively each implant must be checked for correct engagement of the liner in the metal back prior to the definitive reduction of the prosthesis.

The second disadvantage of CoC bearings can be the occurrence of noises such as squeaking. Similar to ceramic liner fractures, there is a great variety of incidence (from 0% to 35%) among different metal back manufacturers reported in the literature.[62,63] Several risk factors have been identified, such as age, obesity, activity level and acetabular component positioning.[64-66] The perception of European surgeons is generally that this event is overestimated by colleagues practising outside Europe. In our clinical practice, we notice frequent cases of post-operative noises caused by the separation of the head from the liner due to post-operative soft-tissue laxity, such as clicking, knocking, popping and snapping, that resolve spontaneously in a few weeks, with only a few occasional typical squeakers. In these cases, the noise is caused by the friction of the components. The retrievals show ceramic grains detached from the head and the liner, which means dulling of the surface, edge-loading and wear (45 times greater than silent retrievals).[67,68] The occurrence of a new delayed noise in a ceramic joint, particularly if linked to pain and malposition, must be carefully considered as it can be caused by breakage and wear of the ceramics that do not normally improve.[69] Nonetheless, the phenomenon has a multifactorial origin, sometimes with conflicting features from published studies. The outcome and patient satisfaction are not affected.

For the aforesaid risks linked to malposition and soft-tissue balancing, the use of CoC has a possible contra-indication in our practice in young patients, in the few cases when it can be difficult to reach the correct orientation of the acetabular component and off-set, such as severe developmental dysplasia of the hip or post-traumatic acetabular deformity. Patients showing weakness of the pelvic

muscles, soft-tissue laxity or excessive range of movement should also be considered at risk.[70] In our clinical practice, CoC is the bearing of choice in younger and more active patients.

Metal on metal

Metal on metal THA has a long history which began in the 1950s and 1960s in the United Kingdom with McKee-Farrar. In the 1980s, small MoM heads (28 mm and 32 mm) by Weber and Semlitsh became quite popular, even if they never gained a major role in the market. Acceptable results are reported with small MoM heads both by registries[3] and clinical studies at medium- to long-term follow-up.[71-74] Unfortunately, due to the high rate of failure and of adverse reactions to metal debris following the MoM big heads introduced in the middle of the 2000s and despite the early favourable outcome of hip resurfacing, MoM THA is nowadays almost entirely abandoned by surgeons and completely withdrawn from the market by manufacturers, including small heads. This bearing surface is no longer an option and the issue nowadays is how to follow-up patients implanted with MoM in the past.[13]

Conclusions

THA is overall a very successful procedure. The long-term survival and satisfaction of patients is linked to the proper bearing surface selection. The surgeon has a responsibility to make a wise choice, based on a comprehensive knowledge of the features of the selected bearing.

Based on the above-mentioned concepts and departmental experience, our choice of indication regarding the articulation in primary standard cases of THA has not changed since 2004. It is:

- below the age of 60 years: CoC (32 mm or 36 mm depending on the acetabular component size and on the metal back thickness; 40 mm is selected nowadays only in cases of large acetabula at higher risk of dislocation in the middle-aged population but not in very young patients);
- over the age of 65 years: CoXLPE (28 mm, 32 mm or 36 mm depending on the acetabular component size and on the risk of dislocation of the patient. In high-risk patients, dual mobility acetabular components are used);
- between 60 and 65 years: depending on the patient's activity; CoC is selected for more active and demanding patients;
- weight and body mass index do not influence the choice of the bearing, whilst in cases with major anatomical deformities, pre-operative high range of movement and soft-tissue laxity, CoC is used carefully – even if the patient is young.

MoXLPE is, of course, a valid alternative bearing option, since as yet there is no long-term evidence on the superiority of one bearing surface over the others among the three best performing PEs (MoXLPE, CoXLPE, CoC). We personally do not see any reason for using a metal head instead of a ceramic one other than cost.

When choosing the surface bearing, the surgeon must keep in mind that not all XLPEs are the same; the dimension changes with different acetabular components and head size but a minimum thickness must be preserved. Also, the ceramics are not always the same, and in the case of CoC the metal-back features (thickness, shape, surface finishing, press fit) and implantation tools can make a great difference. These features differ from one brand to another. Concerning hard bearings, clinical studies on large numbers and registry data are not yet able to evaluate whether wear performances are influenced by surgical technique, the handling and the position of the components, the acetabulum size, the hardness of the bone, the presence of osteophytes, the soft-tissue balancing or restoration of the anatomy. For these reasons, proper training for the surgeon who is willing to use hard bearings such as ceramics should be mandatory.[75]

In conclusion, a comprehensive knowledge of the characteristics, advantages and drawbacks of each bearing surface is essential for surgeons who routinely perform THA. This, along with personal experience, will help in selecting the best coupling for each patient in order to provide the best long-term survivorship of the prosthesis. In our experience, CoC in young and active patients (for the higher wear resistance and biocompatibility) is a good option. CoXLPE and MoXLPE are a valid option for 'older' patients (more 'forgiving' bearings, and good results are reported at 15 years). Moreover, surgeons must remember that what makes the difference is not just the material, but the correct surgical technique and handling of the components – mainly the positioning of the implant.

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