5 points on

Bearing Surfaces in Hip Arthroplasty

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Despite the undisputed role of total hip arthroplasty (THA) in restoring function and mobility to patients with end-stage hip osteoarthritis, the longevity of the artificial joints is limited. In other words, with longer follow-up, some deterioration is evident.[1] As yet, the most notable factor limiting the longevity of hip arthroplasty, particularly in young, active individuals, is wear of the bearing surface and the ensuing aseptic loosening.[1,2] The release of wear particles, mostly from the articulating bearing surfaces, activates a complex inflammatory pathway that leads to loosening of the prosthesis and osteolysis.[3] The role of the bearing surface has become even more important as patients undergoing arthroplasty seek high-performance prostheses to meet their expectations.

Since joint arthroplasty was first introduced, surgeons and engineers have made adjustments to try to increase its longevity and improve outcomes. One extremely important development is the introduction of a new generation of bearing surfaces. Improvements in design, advancements in manufacturing, and introduction of alternative bearing surfaces have positively affected THA outcomes over recent decades. Introduction of bearing surfaces with better wear characteristics led to a decline in the release of biologically active wear debris and tremendously reduced wear-related failures. Furthermore, availability of better bearing surfaces with increased resistance to wear has allowed orthopedic surgeons to use larger femoral heads, which in turn has led to a substantial decline in the incidence of instability after hip arthroplasty.[4,5]

The conventional low-friction metal-on-polyethylene (MOP) bearing surface, which has served our patients so well, is increasingly being replaced by the newer generations of bearing surfaces. However, these modern bearing surfaces are not without their own problems.

1 Why replace old bearing surfaces?

Although extremely successful and durable, one of the "older" and most commonly used bearing surfaces, low-friction ultra high molecular-weight polyethylene (UHMWPE), was found to have significant limitations. One of the major problems with this surface is its wear characteristics. Cyclic loading of the hip, placing forces across the UHMWPE surface, generates wear particles that engender the inflammatory process that leads to aseptic loosening and osteolysis. To increase the longevity of the hip prosthesis, particularly in the young, orthopedic surgeons were compelled to use thicker polyethylene and smaller femoral heads, resulting in a higher incidence of dislocation. The thinner UHMWPE was found to have reduced mechanical properties, bringing about accelerated wear of this surface and dire consequences.[6] This issue became particularly prevalent with the rise in use of cementless acetabular components, in which the presence of a metal shell limits the thickness of the polyethylene liner. Another problem with the use of uncemented acetabular components was the suboptimal locking mechanism of some designs, which allowed motion of the liner inside the acetabular shell, leading to backside wear.[7,8]

Another conventional bearing surface is metal-on-metal (MOM). Among the articular couples in use, MOM-THA has the longest clinical history, dating back to the late 1930s.[9] Originally, the MOM surface was stainless steel, a material now recognized as poor for articular surfaces. In the 1960s, a cobalt-chromium alloy was used to manufacture the Ring and McKee-Farrar MOM hip prostheses that were in widespread clinical use.[9] By the mid-1970s, owing to some concerns, charges against the MOM prosthesis, and the success of the Charnley prosthesis, polyethylene came to dominate the scene, and metal bearings were aban-

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Figure. Metal-backed ceramic acetabular component and fractured ceramic femoral head.

doned in favor of their polyethylene counterparts.[9,10] As time passed, several retrospective studies and analysis of retrieved MOM prostheses showed early failures of first-generation MOM bearings were caused by poor surface finish, irregular geometry, errors in surgical techniques, inadequate clearances, and impingement originating from inappropriate design. In comparisons of wear rates only, however, run-in and steady-state wear rates were found to be much lower for MOM bearings than for Charnley prostheses.[9-11] The remarkable lower linear and volumetric wear rates of MOM bearings were found in both hip simulator and clinical retrieval investigations. Dark tissue staining and osteolysis, found on failed prostheses, appeared to be associated with impingement or with loose components rather than with well-functioning implants.[11]

The clinical performance of the first-generation ceramic-on-ceramic (COC) bearing surfaces in THA began in the 1970s in Europe. Similar to what occurred with first-generation MOM bearings, the imperfect design, deficient fixation methods, and poor quality of materials of early COC couples were associated with impingement, component fracture, and a high rate of implant loosening. Ceramic materials are prone to catastrophic mechanical failure because they have no ductility when subjected to mechanical stress in tensile or impact loading (Figure). When ceramic materials fracture, virtually complete revision is mandatory, and in the majority of cases a simple change of the ceramic head and liner is inadequate.[12] The ceramic components do not tolerate malpositioning well, and suboptimal positioning accelerates the wear process and leads to early failure.

Zirconia ceramics degrade and produce excessive wear attributable to phase transformation and resultant surface roughening. In recent years, oxidized zirconium with a metal core and abrasion-resistant ceramic surface has been introduced with advanced resistance to surface roughening and superior frictional features. However, the available clinical follow-ups are too short to confirm the in vitro results.

2 What are the approaches to reducing wear particles?

Improving wear resistance of polyethylene

In the late 1990s, the first generation of highly cross-linked polyethylene (HXPE) was introduced in an attempt to minimize polyethylene wear debris. HXPE was manufactured using chemical methods or irradiation (gamma or electron-beam). Although radiation at higher doses generates more cross-linking and superior wear resistance, the ultimate tensile strength, plasticity, and resistance to fatigue-crack propagation decrease, which makes the polyethylene susceptible to early failure.[13] The recommended dose of gamma radiation for induction of cross-linking with an optimal balance between wear resistance and mechanical efficiency is 5 to 10 Mrad. Irradiation also creates free radicals, which, if retained, can have a detrimental effect on the material by causing oxidative degradation and subsequent accelerated polyethylene wear. Hence, strategies to remove the generated free radicals, for example, by a process called quenching, are implemented during manufacturing. Sterilization of polyethylene in air has also been abandoned, as it results in free radical generation. Final sterilization is done with ethylene oxide or gas plasma rather than radiation to avoid reintroducing free radicals.

In contrast to conventional UHMWPE, HXPE with improved wear resistance allows larger femoral heads to be applied against thinner polyethylene acetabular liners with succeeding increased range of motion, decreased frequency of dislocation, and reduced impingement without increasing volumetric and even third-body wear.[4,14,15]

New generations of MOM bearing surfaces

In the late 1980s, second-generation MOM prostheses emerged and started gaining popularity in THAs and resurfacing arthroplasties. After the role of the polyethylene particle and resultant inflammation in the initiation of loosening was clarified, the concept of aseptic loosening by virtue of high frictional torque produced with MOM prostheses faded. Meanwhile, engineers fabricated highly polished metal bearing surfaces reducing frictional resistance.

It is estimated that the number of metal particles generated annually is 13 to 500 times larger than the number of polyethylene particles produced from a traditional MOP implant. However, the metallic particulates are on average 100 times smaller than polyethylene debris and therefore too small to elicit a foreign-body giant cell response to the extent that polyethylene particles do.[9,14,16,17] Supposedly, MOM designs have a lower incidence of osteolysis and aseptic loosening. Although these bearings show third-body wear, just as polyethylene does, their unique self-polishing smoothes scratches over time.

The all-metal couples with larger femoral heads not only exhibit more stability and wider range of motion, similar to other large-diameter articulating couples, but they demonstrate less wear and more aptitude to form uniform and

Table. Reported Survivorship for Various Bearing Couples

Authors	Bearing Couple	Follow-Up (y)	Implant Survivorship (%)	
			Revision for Any Reason	Revision for Aseptic Loosening
Berry et al[27] (2002)	Metal-on-polyethylene (Charnley)	25	80.9	86.5
Mullins et al[29] (2007)	Metal-on-polyethylene (Charnley)	30	73.3	—
Brown et al[30] (2002)	First-generation metal-on-metal (McKee-Farrar)	25-28	74.4 (infection excluded)	—
Eswaramoorthy et al[31] (2008)	Second-generation metal-on-metal (Metasul)	10	94	99 (acetabular component) 100 (femoral component)
Hamadouche et al[32] (2002)	First-generation alumina-on-alumina	20	68.3	—
Lusty et al[28] (2007)	Third-generation alumina-on-alumina	7.5	96	99

thicker lubrication film. Better clearance of the new MOM articulations allows the lubrication film to be readily formed.

Advances in ceramics

Regarding the materials and designs, manufacturing of the COC prosthesis has been dramatically improved. The more recently developed alumina-on-alumina implants have improved material grain sizes, purity, sintering techniques, implant design, and, ultimately, clinical reliability.[14] The smaller grain sizes, lower porosity, and high purity achieved by modern manufacturing techniques have drastically increased the quality of the new generation of ceramics. These ceramics show excellent biocompatibility, "wettability," and high resistance to wear and surface scratches and can be fabricated with larger femoral heads for better stability. Being harder than usual allows these ceramics to withstand third-body wear caused by bone and cement particles found in articulating surfaces. Their wettability is better than MOM's owing to their hydrophilic feature, which ensures that synovial fluid is uniformly distributed over the entire bearing surface.[18]

3 What are the concerns regarding modern bearing surfaces?

Patients with any MOM hips have elevated levels of cobalt and chromium ions in their blood and urine. In addition, the metal particles appear in regional lymph nodes, bone marrow, the liver, and the spleen. It should be emphasized that there are multiple metal ion sources besides articulating bearing surfaces, and thus elevated metal ion levels occur even in MOP combinations, though not to the same degree as in MOM bearings.[19]

The incidence of metal hypersensitivity is higher in patients with MOM prostheses, especially poorly functioning prostheses, than in the general population.[20] An aseptic lymphocytic-dominated vasculitis-associated lesion (ALVAL) has been found in the periprosthetic tissues of hips with MOM implants.[21] This immunologic, type IV delayed hypersensitivity response should be suspected if pain, radiolucent lines, or osteolysis develops in a patient with MOM articulation and infection has been excluded.[21] This diagnosis is strongly supported by development of rapidly increasing osteolysis and radiolucent lines and occurrence of a joint effusion.[21]

Studies have yet to determine the clinical significance of higher rates of hypersensitivity to metallic biomaterials. Furthermore, the mutagenicity and carcinogenicity of the metal ions released from these bearing surfaces remain undetermined.[19,20] Further long-term surveillance studies are needed to resolve these issues. Lack of scientific data precludes use of MOM prostheses in women of childbearing age and in patients with chronic renal failure or perhaps any underlying disease rendering the patient susceptible to renal dysfunction.[14] In these circumstances, use of bearings that do not pose a risk for ion release (eg, ceramics) seems more prudent.

Although all-ceramic bearings have the lowest in vivo wear rates, several concerns persist, including continued risk for fracture, potential for wear of some ceramic articulations, generation of debris from new modular interfaces, liner chipping during insertion, impingement and neck damage, squeaking, and fewer head-size options.[12,22,23] Most COC systems have only one head diameter per cup size and only one liner type and, therefore, fewer options for liners and heads. It is valuable to have more options in order to equalize limb length and maximize stability during THA. Not having these options may be the most substantial disadvantage of COC-THA.[12]

Fracture risk, unique to ceramics, is low, especially with the modern generation, which is proof-tested by loading before release. Therefore, defective bearing components with increased risk for fracture are discarded. Fracture of a ceramic component requires immediate revision arthroplasty and introduces the difficult removal of all ceramic fragments to prevent subsequent third-body wear. In most ceramic systems during the revision surgery, the previous taper should not be used for a new ceramic head because the possible tensile hoop stress at the head taper surface might cause head fracture. Unlike the other ceramics, oxidized zirconium lacks the vulnerability to brittle fracture attributable to the metallic core. Nevertheless, it might be damaged during dislocation and closed reduction maneuvers.[24]

Careful insertion of ceramic liners into the shell is crucial to reduce the probability of liner chipping.[12] Because of the sensitivity of the hard-on-hard bearing surface to malpositioning, every effort should be made to ensure appropriate positioning of components.[12,18] Proponents of COC bearing surfaces believe that the higher cost of these implants is offset by an overall reduction in osteolysis and subsequent need for revision surgery. Longer follow-up of these bearing surfaces is needed to prove or refute their effectiveness in reducing osteolysis.

Hard-on-hard articulations can make noise, mainly squeaking or clicking, during specific patient activities. This noise bothers some patients.[25,26] The exact etiology and long-term consequences of squeaking remain largely unknown. The numerous possible causes include femoral head microseparation and subluxation, impingement, stripe wear, edge loading, entrapment of third-body wear debris, disruption of fluid film lubrication, defective manufacturing, and mismatched ceramic bearings.[26]

4 What are the available results?

The Table summarizes the survivorship of different bearing couples. Although long-term outcomes of conventional bearing surfaces (eg, MOP) are known, those of alternative modern-generation bearing surfaces are yet to be determined. The Table shows the longevity of the various bearing surfaces that have been evaluated. That numerous factors besides bearing couples govern implant longevity should be kept in mind when interpreting data pertinent to survivorship. There are numerous reports on the long-term outcomes of THAs using metal-on-conventional-polyethylene as the bearing surface of choice.[1,27] Outcomes of the latter bearing surface, however, are not as optimal in active and young patients, and a higher incidence of failures has been reported.[27] The retrospective studies have shown implant longevity of first-generation MOM designs comparable to that of Charnley MOP designs.[14] The clinical studies have not indicated superiority of second-generation MOM to MOP total hip prostheses with regard to implant survivorship.[11] Given the advantages and disadvantages of all available bearings, modern COC, MOM, and metal-on-HXPE are three viable options for longer durability, but they all still require further confirmation by long-term clinical performance. The recent studies on the short- and medium-term clinical outcomes of third-generation alumina ceramic have shown an extremely low incidence of osteolysis, wear, and failures.[28] The long-term results of recently introduced alternative bearing surfaces remain to be seen.

5 The future

Advances in design and manufacturing of materials in general and bearing surfaces in particular, combined with improvements in surgical techniques (eg, use of navigation, which potentially allows better positioning of components), are likely to continue. The newly generated materials are likely to have better tribologic properties withstanding repeated forces. Newer generations of HXPE, MOM, ceramic, and metal-on-ceramic bearing surfaces are being developed. In addition, coating bearing surfaces with materials such as amorphous diamond may contribute to further reduction of wear and ion release. New bearings, with a ceramic femoral head on a metal acetabular insert, have wear characteristics similar to those of COC bearing surfaces and potentially reduced risk for component fracture.

Engineered for higher strength, alumina matrix ceramic incorporates small zirconia grains. This modification improves fracture toughness and crack resistance and enhances wear behavior even under severe microseparation wear testing.

New strategies for reducing free radicals in HXPE continue to be developed. These efforts include addition of antioxidative but biocompatible materials, such as vitamin E (α-tocopherol).[33]

We are likely to witness further accomplishments in the field of joint arthroplasty in general, and reduction of wear in particular, that will further enhance the performance of an already successful joint arthroplasty in patients with disabling arthritis.

Authors' Disclosure Statement

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