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Ceramic-on-Ceramic Bearings in Total Joint Arthroplasty. Part 2

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Summary. *Total hip arthroplasty (THA) currently provides durable long-term outcomes, but osteolysis secondary to polyethylene wear debris remains a fundamental cause of aseptic loosening and revision. Conventional polyethylene failed to provide a suitable bearing for young active patients requiring joint replacement because of the significant demands they place on such bearings. Strategies to reduce friction and wear debris lead to the development of ceramic bearings in THA. The next decade is unlikely to see a paradigm shift in the materials used for THA. Instead, the challenges will be dedicated to improve surgical technique in terms of component orientation to improve reproducibility and achieve superior patient outcomes. The optimum bearing surface is one with very low wear rates, a low coefficient of friction, scratch resistance, and is biologically inert. It is also one that can safely accommodate larger femoral head sizes to minimize dislocation rates without damaging the taper junction. Such a material already exists with modern ceramic bearings.*

Key words: *total hip arthroplasty; total knee arthroplasty; ceramics; polyethylene; bearing wear.*

Total hip arthroplasty (THA) currently provides durable long-term outcomes, but osteolysis secondary to polyethylene wear debris remains a fundamental cause of aseptic loosening and revision. Conventional polyethylene failed to provide a suitable bearing for young active patients requiring joint replacement because of the significant demands they place on such bearings. Strategies to reduce friction and wear debris lead to the development of ceramic bearings in THA.

1. Characteristics of Ceramics

1.1. Material properties

High strength, a high elastic modulus, high fracture toughness, and high fatigue resistance are vital for materials used as articular surfaces in total joint arthroplasty, both to provide mechanical reliability and to resist deformation. These materials should also have high corrosion resistance for bioinertness and biocompatibility. Qualities such as high hardness and good surface finish are essential for long-term wear resistance and low friction in articular surfaces. A low contact angle provides good wetting and lubrication.

Ceramics are crystalline structures in which the atoms are held together by strong ionic and covalent bonds. The strong atomic bonding gives these compounds their characteristic high compressive strength, hardness, and chemical inertness.

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Alumina and zirconia are oxidized ceramics (aluminum oxide [Al_2O_3] and zirconium oxide [ZrO_2], respectively), and their high oxidation level renders them chemically inert, resistant to corrosion, and stable over the long term *in vivo*. These oxides have polar hydroxyl (-OH) groups that promote interaction with aqueous body fluids to provide a lubricating layer.

The crystalline structure of alumina and zirconia also account for their characteristic brittleness, which is associated with low resistance to the propagation of cracks within the material. The brittle behavior of the ceramics is expressed as a low toughness value, which is lower than those of CoCr and titanium alloy [1].

1.2. Fabrication and microstructure

Ceramic bearings are made by heating fine particles or powders of the materials into a porous body of the desired shape, followed by heating to bond particles together. The properties of the bearing are a function of the resulting microstructure.

The microstructure of the bearing is determined by the nature, quality, and distribution of the material grains; the porosity within these grains; and manufacturing variables. Grain homogeneity, purity, and size consistency affect the mechanical properties of the bearing. Higher material density (lower porosity) and smaller grain size will result in superior mechanical properties and strength in the ceramic bearing. Performance also depends on fracture toughness and the design of the implant.

Modern manufacturing methods, such as hot isostatic pressing, can produce ceramic bearings with near-

zero internal porosity and with fine, uniformly sized grains distributed homogeneously throughout the material. The improved reliability of modern ceramics is largely due to improvements in raw materials, manufacturing processes, and implant design [2].

1.3. Brittleness and limitations

Femoral components made of oxidized zirconium have been favored for total knee arthroplasty (TKA) in the United States. Catastrophic failure of an all-ceramic femoral component in TKA has yet to be reported.

The brittleness of ceramics has led to unexpected catastrophic failure of femoral heads *in vivo*. Microscopic flaws (e.g., pores, notches, inconsistencies and scratches) can be introduced during ceramic fabrication or during surface-matching of the finished bearing. With repetitive loading, stress concentration at a material imperfection can start a crack that subsequently migrates, resulting in abrupt failure. In contrast, under similar conditions, metal surfaces undergo plastic deformation and dissipate the applied stress without catastrophic failure.

Catastrophic ceramic bearing failure most commonly occurs in the absence of any identifiable risk factor. Patient obesity, strenuous activity, and trauma have been listed as possible risk factors for the failure of ceramic femoral heads, but these variable loads are well below the fatigue limit of ceramics.

Compressive loads are well tolerated by ceramic bearings, but tensile stress can develop inside the taper bore of a femoral head and result in catastrophic failure. It has been experimentally and clinically demonstrated that tensile loads may be stored as hoop stresses within ceramic femoral heads, leading to delayed failure. Such failures possibly occur because of microscopic damage and stress retention in the bearing, with failure occurring when the internal material stress exceeds its fracture strength [3].

Ceramic femoral heads can survive multiple forceful impactions on a metal trunnion without apparent damage, with fragmentation encountered only after a delay. In alumina acetabular inserts, tensile forces can develop if an eccentrically seated insert is impacted into a metal acetabular shell, resulting in chipping of the insert edge.

There are a number of design variables that can affect tension between the femoral head and the stem taper in THA. In articulations between ceramic and ceramic and between ceramic and UHMWPE, *in vivo* failure can result from the fracture of the ceramic femoral head, fracture of the acetabular liner, or wearthrough and fracture of the UHMWPE acetabular liner. Surgeons must be accurate when inserting the acetabular ceramic liner. Even a malalignment of 5° may result in chipping and cracking of the ceramic. In minimally invasive procedures, this 5° malalignment figure may even be more relevant.

The combination of a high patient body weight, extensive range of motion, and subluxation of the femoral head can led to high friction at the articulation between the femoral head and the rim of the liner, which initiates displacement of the ceramic liner. Subsequent normal gait leads to further displacement of the liner and eventually causes ceramic liner fracture.

The rate of alumina liner damage during surgery, as reported to one manufacturer (CeramTec, Plochingen, Germany), was 0.022% in 2000 and had declined to 0.008% by 2004. The risk of alumina femoral head failure declined from 2% in the 1970s to 0.1% in 1980s and to 0.05% in 1990s. Clinical trials in the United States that began in the 1990s have not yet reported any femoral head failures *in vivo* [4].

Revision hip arthroplasty after a primary hip replacement with ceramic bearings is potentially a large problem. Allain et al. reported a 5-year survival rate of 63% for revision following fracture of a ceramic femoral head [5]. Any ceramic debris remaining after revision surgery acts to produce third-body wear. If a standard metal-on-PE bearing is used in such a revision, there will be very high levels of third-body wear on the PE, with subsequent osteolysis.

Even with metal-on-metal bearings, there are concerns regarding metallosis. Some surgeons have advocated using only ceramic-on-ceramic bearings in such revisions. A revision with simple exchange of bearing surfaces for well-fixed components probably will not be possible if ceramic bearings are to be used at the time of revision [5].

Audible squeaking is a rare problem in THAs with hard-on-hard bearings such as ceramic-on-ceramic or metal-on-metal. The origin of the squeaking sound is multifactorial. One factor is acetabular cup orientation; another is that patients with squeaking hips reportedly tend to be younger, heavier, and taller than patients with silent hips. The hips start squeaking after an average of 14 months. Hips that squeaked with walking had more anteverted acetabular components than those that squeaked with bending or prolonged walking.

Improvements in implant design have overcome some of the limitations of ceramic implants. The junction between the femoral head and the femoral stem critically affects the performance of ceramic femoral heads. The taper material bore depth, the contact area between the bore and the taper, the trunnion-bore distance, and the chamfer at the base can all affect the clinical outcomes of a ceramic head.

Tensile stresses can concentrate at the upper bore corner and can be reduced by increasing the ceramic-metal contact area, increasing the trunnion-bore distance, and centering the contact area on the bore. Thus, different prosthetic neck lengths in a ceramic femoral

head can have varying effects on the risk of catastrophic fracture *in vivo*.

The tapers on modern femoral stems are optimized to fit ceramic femoral heads and avoid stress risers at the taper-bore junction. The Morse tapers optimized for ceramic femoral heads typically have a number of peaks and valleys on the taper surface that are designed to flatten during head impaction, absorbing the applied loads and avoiding stress concentration [6].

Ceramic femoral heads should be implanted on a clean, unused, and undamaged metal taper. Scratching, taper corrosion, or material caught between the taper and the head can lead to stress concentrations and increase the risk of ceramic failure.

2. Ceramics Used for Bearings

2.1. Alumina ceramics

Alumina (aluminum oxide [Al_2O_3]) has been the most commonly used ceramic bearing material in THA. Pure alumina has a very low coefficient of friction, making it an appropriate choice for an orthopedic bearing surface. Alumina has proven biocompatibility, and *in vivo* aging does not affect its material properties. When used in alumina-PE THA articulations, alumina femoral heads reduce PE wear rates; when used in alumina-alumina THA articulations, they can eliminate PE wear entirely.

The role of improved materials, implantation techniques, manufacturing variables, and implant design in reducing the risk of catastrophic failure of ceramic bearing is best illustrated in the development of alumina femoral heads. The risk of catastrophic failure of a femoral head (e.g., BIOLOX *forte;* CeramTec, Plochingen, Germany) is estimated to be between 1/25,000 (0.004%) and 1/10,000 (0.01%) [7].The risk of other adverse outcomes associated with routine THA (e.g., infection, dislocation, revision, and venous thrombosis) is much higher than that of alumina bearing failure.

2.2. Zirconia ceramics

Zirconia (zirconium oxide [ZrO_2])-based ceramics have two to three times more flexural strength and fracture toughness than alumina-based ceramics do and thus are among the most fracture-resistant ceramics available. They were introduced to reduce the risk of catastrophic failures with alumina heads while retaining superior wear properties. However, pure zirconia is not used as a bearing material because it is unstable: it transforms from one form to another, and the shape and volume changes render it vulnerable to cracking.

Phase transformation of zirconia can be controlled by adding stabilizing materials such as magnesia (magnesium oxide [MgO]), quicklime (calcium oxide [CaO]), and yttria (yttrium oxide [Y_2O_3]). This process is called transformation toughening. Controlled phase transformation has been used to develop different zirconia compositions for orthopedic bearings, such as tetragonal zirconia polycrystal (TZP), partially stabilized zirconia (PSZ), and zirconia-toughened alumina (ZTA).

Tetragonal zirconia polycrystal

TZP is the strongest and toughest of zirconia-based ceramics, with optimal material density, fine grain size, and no strength-limiting flaws. Catastrophic wear is a possibility with zirconia-alumina and zirconia-zirconia bearing couples.

Yttria-stabilized TZP (Y-TZP) femoral heads have been approved for use with PE or cross-linked PE (XLPE) acetabular inserts in THA to reduce wear. However, Y-TZP has two major practical drawbacks: (1) instability that leads to uncontrolled phase transformation and cracking in the heat and moisture of autoclave conditions and (2) time-dependent degradation of the material even at physiologic temperatures.

In theory, these adverse properties can be controlled by modifying the grain size and powder composition; in practice, the multiple uncontrolled variables of the *in vivo* environment can lead to catastrophic failure of Y-TZP femoral heads. A single change in the manufacturing process of commercial Y-TZP femoral heads can lead to unexpectedly high premature failure rates and, ultimately, to the withdrawal of all Y-TZP from orthopedic applications.

Partially stabilized zirconia

Partially stabilized zirconia (PSZ) usually contains magnesia as the stabilizing additive (i.e., Mg-PSZ). Mg-PSZ was among the first zirconia ceramics introduced in the United States because of its toughness and smooth surface. Mg-PSZ ceramic femoral heads are available in the United States for ceramic-PE articulations (e.g., from BioPro, Port Huron, MI), but their use is not widespread.

Unlike Y-TZP, Mg-PSZ is resistant to strength degradation in a moist environment, even at autoclave temperatures. Specimens retrieved from THAs have also shown that femoral heads made of Mg-PSZ do not undergo phase transformation *in vivo*. However, clinical data with Mg-PSZ are sparse, and the grain size distribution and mechanical properties of Mg-PSZ are typically inferior to those of well-fabricated Y-TZP in the absence of any material degradation [8].

2.3. Alumina-zirconia composites

Zirconia-toughened alumina

ZTA is a two-phase material made of zirconia particles dispersed in a dense, fine-grained alumina matrix. It has the hardness of alumina, with improved strength and fracture toughness, and is less susceptible to material degradation than Y-TZP is. Hip simulator tests have shown lower wear rates for ZTA-ZTA THA couplings than for alumina-alumina couplings. However, the clinical data on ZTA are insufficient to establish an advantage over alumina, and experimental aging of ZTA in

Ringer solution has been associated with material degradation and reduction in material strength.

Alumina matrix composite

ZTA can be further modified by adding materials such as strontia (strontium oxide [SrO]) and chromia (chromium [III] oxide [Cr_2O_3]) to fabricate an alumina matrix composite (AMC). These additives react with the alumina matrix to create elongated grains that add strength by providing an additional barrier to crack propagation. Hip simulator testing has shown that the wear rate of AMC-AMC THA couplings is less than those of ZTA-ZTA, alumina-alumina, and even AMC-alumina couplings. Biocompatibility tests have shown that AMC is inert.

THA bearings made from AMC are marketed under the brand name BIOLOX *delta* (CeramTec, Plochingen, Germany). Early trials suggested that BIOLOX *delta* femoral heads may be suitable for articulation against cobalt-chromium (CoCr) acetabular inserts in THA, eliminating the risk of ceramic liner chipping. In addition, large-diameter AMC femoral heads can reduce the risk of catastrophic failure and THA dislocation. Because AMC is relatively new, additional study is warranted to assess its reliability and determine whether it has significant advantages over the more widely used BIOLOX *forte* alumina bearings. Yoo et al. reported promising results at 10 years' follow-up [8].

2.4. Nonoxide ceramics

Silicon carbide (SiC) and silicon nitride (Si_3N_4) are nonoxide ceramics. Compared with alumina, silicon carbide has increased strength and hardness and comparable fracture toughness. However, its corrosion and wear behavior in the physiologic environment are unknown. Because its fracture toughness is similar to that of alumina, pure silicon carbide probably has no particular advantage over alumina.

Silicon nitride, on the other hand, has material properties that are compatible with orthopedic bearings. Material testing of silicon nitride composites has shown them to have 50% more strength and fracture toughness than current ZTA and AMC devices, and wear tests with this material have shown excellent wear characteristics.

The mechanical and wear properties of silicon nitride could allow CoCr-ceramic couplings in THA, combining the safety and advantages of CoCr femoral heads with lower wear rates. Experimental wear rates of silicon nitride ceramic-ceramic and ceramic-CoCr couplings are similar to those of alumina THA bearings.

Long-term *in vivo* exposure to silicon nitride does not lead to toxicity, mutagenicity, allergenicity, or carcinogenicity. Silicon nitride bearings for arthroplasty applications, investigated by Amedica Corporation (Salt Lake City, UT), may offer additional bearing options in the future [4].

3. Related Wear-Reducing Technologies

3.1. Hard coatings on metals

The wear properties of metal can be improved by depositing hard materials on the metallic surface as a coating. The techniques used to accomplish this have included nitrogen ion implantation, thermal diffusion, and vapor deposition of a nitride coating. Many of these wear strategies have not proved viable in clinical applications. For example, whereas titanium nitride coatings improve the hardness and wear characteristics of metal bearings, their performance under critical stress conditions *in vivo* is unpredictable.

Applying thin diamondlike carbon coatings to femoral heads is another material technology that could improve the wear performance of metal bearings. Amorphous diamond coatings have advantageous properties, such as low friction and high resistance to wear and corrosion; such coatings are also resistant to surface abrasion. Although experimental data are encouraging, the performance of diamond-coated metal bearings *in vivo* is still unknown. Bearings with thin diamond coatings are being developed and tested for clinical trials by Diamicron (Orem, UT) [5].

3.2. Surface modifications of metals

Surface transformation of metal to oxidized zirconium is another method of reducing PE wear in THA and TKA. A wrought zirconium alloy (zirconium with 2.5% niobium) is oxidized by thermal diffusion to create a 5-μm oxidized zirconium layer at the articulation (Oxinium; Smith & Nephew, Memphis, TN).

The surface oxide represents a transformation of the metal into zirconium oxide ceramics, which can be polished to a smooth surface. Compared with other surface modification technologies, the oxidized zirconium layer has excellent cohesion and adhesion, and it generates less wear against PE than CoCr does.

A major advantage of this approach is the interchangeability of femoral heads during revision surgery, without the need for concern about the brittleness of a ceramic bearing. Limitations of this technology include the relatively modest reduction in PE wear rates and the susceptibility to scratching, both of which may be related to the surface oxide's lower surface hardness in comparison with alumina [5].

3.3. Nanoceramics and ceramic nanocomposites

Particulate wear generated by ceramic-on-ceramic bearings can be further reduced by using ceramic with ultrafine or nanoscale grain sizes – or, better still, ceramic nanocomposites. Strength, hardness, fracture toughness, and wear resistance are improved with reduced grain sizes, particularly sizes in the nanoscale range. Alumina-silicon carbide nanocomposite has superior wear properties. Alumina-zirconia, alumina-titania (titanium [IV] oxide [TiO_2]), zirconia-alumina, and silicon nitride–silicon carbide nanocomposites are under investigation [6].

4. Indications and Contraindications

In general, ceramic bearings are indicated for THA and TKA in inflammatory and noninflammatory degenerative joint diseases such as osteoarthritis, posttraumatic arthritis, or secondary arthritis and avascular necrosis (AVN). Today, given the state of technology regarding ceramic bearings, their advantages, and their disadvantages, most surgeons use specific indications when choosing ceramics.

Along with metal-on-metal bearings, ceramic bearings are referred to as alternative bearings or hard bearings. The advantage of such bearings is that they remove PE from the articulation entirely, thereby eliminating PE wear debris as a potential source of wear-related problems in the long term. The only rationale for using such bearings in hip surgery is to increase the longevity of the arthroplasty, while allowing an active lifestyle for the patient. In making this choice, the surgeon has to consider the limitations of the bearing system as well.

In view of the higher costs and extreme wear resistance of ceramics, the commonly accepted indication for ceramic bearings is in young and active patients who seek hip replacement. This is the patient population for whom the wear reduction achieved with ceramics is likely to have the most enduring benefits. No precise age cutoffs exist, but surgeons typically balance chronologic age, physiologic age, patient activity level, and medical comorbidities when deciding whether to use ceramic bearings during THA [5, 9].

It follows that ceramic bearings generally are not indicated for elderly and infirm patients whose longevity or activity level is limited. These patients will derive no particular benefit from a ceramic bearing system and are better suited for a traditional metal-PE bearing couple, which almost certainly will outlast them.Again, there is no exact age or activity cutoff; the decision depends on the surgeon's judgment.

In some patients, sizing considerations may necessitate the use of an acetabular component with a relatively small diameter. For such patients, a large-diameter ceramic femoral head may not be an option. Large-diameter femoral heads reduce the risk of hip dislocation and are favored in modern hip surgery. However, because of design limitations related to material properties, ceramic bearings are available in only a limited range of femoral neck lengths and head diameters; thus, a surgeon choosing a larger-diameter femoral head may have no choice but to use a metal head.

Likewise, ceramic acetabular inserts are not yet available in constrained designs; if a particular patient presents concerns related to hip stability, ceramic bearings may be contraindicated.

Ceramic bearings are contraindicated in foreign body sensitivity, obesity, infection, sepsis, osteomyelitis, osteoporosis, and osteomalacia. Certain types of pelvic anatomy may preclude the use of standard hemispherical acetabular components, in which cases ceramic bearings may not be usable. In cases of known hip instability, ceramic bearings are generally contraindicated, because recurrent hip dislocations with ceramic femoral heads can lead to metallosis and wear debris accumulation.

In revision THA, ceramic femoral heads should not be used on existing tapers on which a femoral head previously has been impacted. The risk is that the taper has already been deformed microscopically, and unless the new femoral head mates perfectly with the used taper, there is a risk of focal stress concentrations that may result in femoral head failure [9].

Whenever a ceramic bearing is used, it is vital to ensure that the taper is designed to accept that particular bearing; mixing and matching of components between manufacturers should be avoided. Tolerances are significantly tighter with ceramics than they are with metals, and modern taper systems are optimized for use with specific ceramic bearings. Accordingly, the surgeon must be aware of the nature of the taper on which the ceramic bearing will be placed.

Conclusion

The next decade is unlikely to see a paradigm shift in the materials used for THA. Instead, the challenges will be dedicated to improve surgical technique in terms of component orientation to improve reproducibility and achieve superior patient outcomes. The optimum bearing surface is one with very low wear rates, a low coefficient of friction, scratch resistance, and is biologically inert. It is also one that can safely accommodate larger femoral head sizes to minimize dislocation rates without damaging the taper junction. Such a material already exists with modern ceramic bearings.

Conflict of interests. The author declares no conflict of interest towards the present article.

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Керамо-керамічні пари тертя в тотальному ендопротезуванні суглобів. Частина 2

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Резюме. *Тотальне ендопротезування кульшового суглоба забезпечує довгострокові результати, але остеоліз, що виникає внаслідок зношування поліетилену, залишається основною причиною асептичної нестабільності та ревізії. Звичайний поліетилен не зміг забезпечити відповідний темп зношування для молодих активних пацієнтів, які потребують тотального ендопротезування через значні навантаження, які у молодих хворих діють на пари тертя у штучному суглобі. Стратегії зменшення тертя та зношування призводять до розвитку керамічних пар тертя для тотального ендопротезування суглобів. У наступне десятиріччя навряд чи відбудеться зміна парадигми у матеріалах, що використовуються для тотального ендопротезування суглобів. Рішення будуть спрямовані на удосконалення хірургічної техніки з точки зору орієнтації компонентів, щоб покращити умови функціонування ендопротезів і досягти кращих результатів для пацієнтів. Оптимальні поверхні штучного суглоба – це поверхня з дуже низьким рівнем зносу, низьким коефіцієнтом тертя, стійкістю до подряпин і біологічною інертністю. Вони також можуть дозволити збільшити розмір головки стегнової кістки, щоб мінімізувати частоту вивиху без ушкодження конічного з'єднання голівки і ніжки протеза. Таким матеріалом, що задовольняє сьогоднішні вимоги до суглобових поверхонь штучних суглобів, є сучасна кераміка.*

Ключові слова: *тотальне ендопротезування кульшового суглоба; тотальне ендопротезування колінного суглоба; кераміка; поліетилен; тертя поверхонь.*