Alternative Bearing Surfaces for Total Joint Arthroplasty

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Abstract

The biologic response to polyethylene particulate debris generated from metal-on-polyethylene bearing surfaces is thought to be largely responsible for periprosthetic osteolysis and aseptic loosening in total joint arthroplasty. As a result, there has been an interest in developing polyethylene with improved wear characteristics, as well as a renewed interest in alternative bearing surfaces for total joint arthroplasty, including ceramic-polyethylene, metal-metal, and ceramic-ceramic articulations. These alternative surfaces have demonstrated less friction and lower wear rates than metal-on-polyethylene bearing surfaces in both clinical and laboratory experiments. Clinical results, although only short- to mid-term, have been encouraging. Alternative bearing surfaces, with lower wear rates and less particulate debris formation, may have the potential to improve total joint arthroplasty survivorship by decreasing periprosthetic osteolysis, especially in younger, high-demand patients.

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The articulating bearing surface most commonly used for total hip arthroplasty (THA) in the United States is a metal femoral head manufactured of either stainless steel or cast or wrought cobalt-base alloy articulating against a high-molecular-weight polyethylene acetabular component. In use since 1961, metal-on-polyethylene bearings have demonstrated good to excellent clinical results and are considered the standard against which all alternative bearings must be compared.[1] However, wear of the polyethylene (75 to 250 μm/yr) and resultant periprosthetic osteolysis are major long-term concerns that affect implant longevity, particularly for young, active patients.[2,3]

Periprosthetic osteolysis and aseptic loosening are thought to be primarily due to the body's reaction to polyethylene particulate debris generated from the metal-on-polyethylene articulation. Accumulation of particulate debris can result in an aggregation of macrophages that attempt to phagocytize it. The ensuing chronic inflammatory response is characterized by the release of lytic enzymes, proinflammatory cytokines, and bone-resorbing mediators, resulting in osteolysis that can cause aseptic loosening and fixation failure.

Current prosthesis design utilizes strategies for minimizing the generation of polyethylene debris and its damaging effects, such as avoiding the use of large-diameter femoral heads, improving polyethylene quality, avoiding excessively thin (<5 mm) polyethylene, increasing the stability of modular connections, and avoiding the use of metal-backed cups with screw holes.[4] As alternatives to metal-on-polyethylene bearings, ceramic femoral heads have been used to articulate with the polyethylene, or the polyethylene has been eliminated entirely by the use of either metal-on-metal or ceramic-on-ceramic bearings. In the laboratory and clinical setting, these alternative bearings produce less particulate debris and incite a less intense chronic inflammatory reaction than standard metal-on-polyethylene articulations.[5,6]

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Ceramic-on-Polyethylene Bearings in THA

The most common alternative bearing used for THA is the ceramic-on-polyethylene articulating surface. The ceramic femoral head can be made of either aluminum oxide or zirconium oxide. Alumina ceramics were the first to be introduced for use in total joint arthroplasty, but there were clinical problems due to their brittleness and propensity to fracture. To combat this problem, zirconia ceramic, with improved toughness and wear properties, was introduced into use in the United States in 1989.[7] Zirconia ceramic exhibits one fifth the wear of alumina ceramic on polyethylene, and its greater toughness permits the use of femoral heads with smaller diameters than those made of alumina. Nevertheless, cases of fracture of zirconia ceramic femoral heads have also been reported.[8]

Clinical and laboratory wear rates for ceramic-on-polyethylene bearings are generally considerably less than those for metal-on-polyethylene bearings. Wear rates for ceramic-on-polyethylene bearings have varied in the literature, ranging from 0 to 150 μm/yr and averaging 10% to 50% less wear than with a standard metal femoral head on polyethylene.[9] Theoretical advantages of ceramic femoral heads over metal femoral heads include the following: (1) Ceramics have superior lubrication properties. (2) Ceramic polishing achieves a smoother surface than can be achieved with metal, decreasing the coefficient of friction of the bearing surface and thus improving wear characteristics. (3) Ceramic femoral heads are much harder than metal femoral heads and therefore less susceptible to third-body wear and scratching of the surface. (4) Ceramics are inert and maintain their surface finish without evidence of ion release.

In contrast, metallic femoral heads undergo oxidation and resultant surface roughening; during motion, the surface can be worn away, leading to metal ion release.[6] Despite the decreased wear rates of ceramic-polyethylene articulations, clinical reports of periprosthetic osteolysis and catastrophic polyethylene wear have also been observed.[9] Currently, there is no evidence of a clinical benefit or reported decrease in revision rates for the ceramic-on-polyethylene bearing compared with a metal-on-polyethylene bearing.[1]

New-Generation Ceramic-on-Ceramic Bearings in THA

In 1970, Boutine was the first to report on the use of an alumina ceramic-on-ceramic bearing for total joint arthroplasty.[10] At about the same time, Mittelmeier also developed a ceramic-on-ceramic bearing for total joint arthroplasty consisting of a threaded noncemented cup and a press-fit femoral stem[11] (Fig. 1). It was demonstrated that ceramics have excellent biocompatibility due to their highly oxidized state, excellent tribologic properties (lubrication, friction, wear), extreme hardness, good surface finish, and biologic inertness.[4]

Early failures with ceramic-on-ceramic articulations, arising from poor implant design and use of low-quality ceramics, dampened the initial enthusiasm engendered by low wear rates in the laboratory.[4] Newer designs display clinical and laboratory wear rates averaging 0.5 to 2.5 μm per component per year, and ceramic quality has been strictly standardized.[1] However, the possibility of brittle fracture and the high cost of the ceramic components are factors that must be considered before their more widespread use.

Fig. 1 The Mittelmeier ceramic prosthesis with a femoral stem. Note the straight distal femoral shaft, corrugation of collar, honeycomb grooves for bone ingrowth, and threaded noncemented acetabular cup.

Factors associated with early failure of the initial ceramic-on-ceramic hip bearings included improper positioning of the acetabular component and small femoral head sizes. Vertical cup placement, which increased contact stresses at the rim of the cup, resulted in localized fragmentation and third-body wear.[12] The use of smaller ceramic femoral heads (<28 mm) also increased localized contact stresses at the acetabular component. Furthermore, the use of poorly designed taper locks that connected the femoral head to the stem resulted in increased junctional hoop stresses, which caused tensile stress and fracture.[7]

The use of the newer-generation press-fit ceramic-on-ceramic bearings allows increased surgical ease in obtaining correct implant positioning. The ceramic bearing insert fits into the acetabular hemispherical shell through a taper lock (Fig. 2). A technical problem with these

Fig. 2 The Secur-Fit hydroxyapatite press-fit ceramic-on-ceramic bearing prosthesis (Osteonics; Allendale, NJ) has a ceramic articulation that attaches to a metal acetabular shell through a taper lock. It is the only ceramic-on-ceramic bearing undergoing clinical trials in the United States and is strictly for investigational use.

all-ceramic conical liners concerns positioning into the metal acetabular shell. The liners are not self-centering, and due to the low angle of the truncated cone and the hardness of ceramic, incorrect positioning during insertion may result in fracture of the conical liner (P. Dalla Pria, MD, written communication, July 8, 1998). While several institutions in the United States are currently conducting clinical trials to evaluate this experimental press-fit design, these newer-generation ceramic-on-ceramic bearings have been used in Europe since 1990. Clinical results at 5-year follow-up have shown that rates of patient satisfaction and radiographic evidence of loosening are similar to those obtained with standard metal-on-polyethylene bearings.[13,14] These studies have demonstrated a 1% incidence of component fracture and incorrect operative positioning of the ceramic conical liner.

The high modulus of elasticity of ceramic has also been linked to the early failure of the all-ceramic acetabular components in THA.[10] Because of the high rigidity and resultant low-energy absorption of ceramic, direct transmission of loads to the periacetabular bone occurs. Early-generation ceramic-on-ceramic hip bearings demonstrated better results in younger patients due to the increased strength of the periacetabular bone.[10] Because the periacetabular bone in elderly patients was osteoporotic, there was decreased tolerance of hip force transmission, which eventually led to acetabular component migration.

To reduce the rigidity of the ceramic-on-ceramic bearing, newer designs have combined the force-dampening qualities of polyethylene with an articulating ceramic bearing[12] (Fig. 3). The alumina articular liner with an outer lining of polyethylene is fitted into a modular metal-back acetabular cup. The polyethylene, with a lower modulus of elasticity, is capable of absorbing and distributing forces to a greater extent than ceramic. The reduction of rigidity offered by the addition of polyethylene may extend the range of indications for use of ceramic-on-ceramic implants to include the elderly with poor acetabular bone stock. Early results from studies with 1-year follow-up are encouraging.[15] Patients' Harris hip scores improved from a preoperative mean value of 47.8 to a postoperative score of 92.6. Follow-up radiographs at 1 year displayed no change in acetabular cup position, and no evidence of wear or loosening.

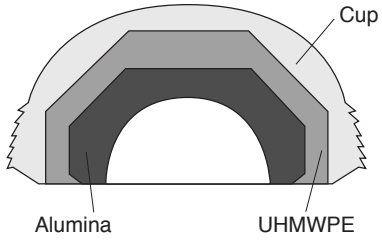


Fig. 3 **Left,** The Contact acetabular cup design has a ceramic articulating surface fitted into a nonarticulating polyethylene liner, which is then fitted onto a metal acetabular shell. This design is not currently available in the United States. **Above,** Cross section through the Contact acetabular cup. UHMWPE = ultra-high-molecular-weight polyethylene. (Courtesy of Paolo Dalla Pria, MD, Lima-LTO, Casiasco PN, Italy.)

New-Generation Metal-on-Metal Bearings in THA

In 1984, Müller and Weber reintroduced the concept of metal-on-metal components with new materials and implant designs.[5,16] Weber fixed a 28- or 32-mm cobalt-chromium-molybdenum inner bearing in the polyethylene insert of a noncemented metallic shell (Fig. 4). At follow-up a mean of 3.5 years after THA, 98 of 100 patients had good to excellent results, and only 4% had evidence of aseptic loosening. Analysis of retrieved femoral heads demonstrated linear wear rates ranging from 4.0 to 5.9 μm per component per year—values similar to the wear rates in the authors' in vitro hip simulator studies. Other studies of metal-on-metal bearings have shown no aseptic loosening at short-term follow-up and consistently good to excellent clinical results.[17,18]

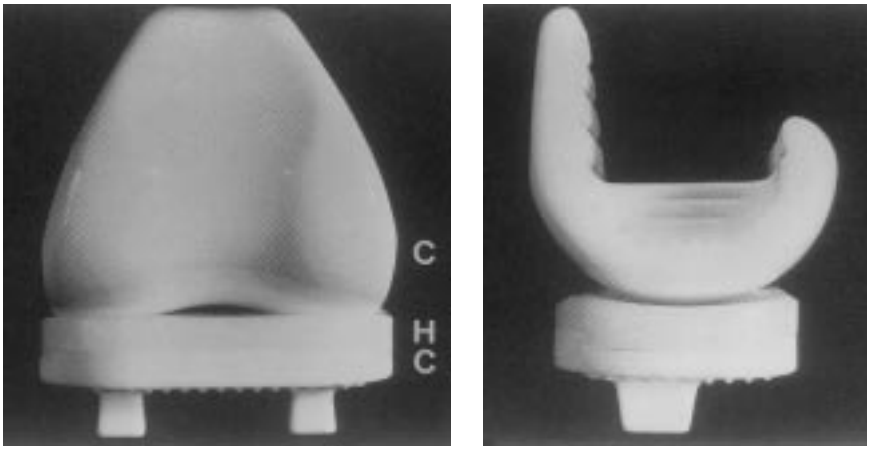
Laboratory data for this new-generation metal-on-metal bearing surface have demonstrated improved tribologic characteristics. Wear tests in hip simulators have demonstrated that new-generation metal-on-metal bearing surfaces generate fewer particles than metal-on-polyethylene articulations.[5] Laboratory wear rates for metal-on-metal bearings are notably lower than those for metal-on-polyethylene bearings, ranging from 2.5 to 5.0 μm per component per year.[19] However, there remain clinical concerns about the possibility of an increased incidence of malignant disorders due to the presence of metallic particles and ions in metal-on-metal THA bearings. Visuri et al[20] concluded that the gross variation in the incidence of different cancers among patients with THA compared with the general population is likely attributable to factors other than the particular implant used.

Clinical trials are currently under way in the United States, but in Europe several metal-on-metal bearing designs are already in use, including the Weber cemented socket, the press-fit acetabular cup of Marchetti, the Wagner noncemented cup, the elastic socket of Spotorno, the Stühmer prosthesis, the Zweymüller prosthesis, and the Müller cemented and noncemented all-metal systems. All these metal-on-metal implants have in common a forged 28-mm CoCr acetabular bearing inserted into an outer polyethylene socket or liner. While the clinical results with early metal-on-metal bearing designs were inferior to those for metal-on-polyethylene bearings,[21] the initial follow-up results of the newer metal-on-metal THA bearings have been encouraging. Longer follow-up is necessary, and continued research in the epidemiology of possible malignant conditions due to metal-on-metal articulations is needed before these implants can be advocated for widespread clinical use.

Fig. 4 Weber THA prosthesis consists of a modular titanium cemented femoral stem with a curved or straight design and a four-layer sintered stainless-steel mesh cup. The articulation consists of a 28-mm CoCrMo alloy femoral head and a CoCrMo metal shell fixed within an outer polyethylene cup. This device is strictly for investigational use and is not available in the United States. (Courtesy of Weber BG: Experience with the Metasul total hip bearing system. *Clin Orthop* 1996;329[suppl]: S69-S77.)

Ceramics and Total Knee Arthroplasty

The recent experience with alternative bearings in total knee arthroplasty (TKA) is much more limited than that with THA. This is due to concerns about the brittle nature of ceramics, their inability to withstand high-impact forces, and the high early failure rates of all metal-hinged total knee replacements.[22] Researchers in Japan have developed a TKA component design that consists of a ceramic femoral component and a ceramic tibial base plate with an articulating polyethylene insert (Fig. 5). Biomechanical tests have demonstrated the ability of these components to sufficiently withstand the forces generated at the knee without fracturing.[22] Laboratory wear studies comparing zirconia ceramic and CoCr femoral components with a 10-mm-thick tibial polyethylene component demonstrated considerably less wear of the polyethylene with the ceramic component.[23] Early follow-up (2 to 4 years) of a cemented alumina posterior cruciate condylar TKA prosthesis with a polyethylene articulating insert demonstrated results similar to those for a metal-on-polyethylene TKA prosthesis, with no evidence of ceramic component fracture.[22]



A B

Fig. 5 Anteroposterior **(A)** and lateral **(B)** views of the KC-1 total knee prosthesis (Kyoto Ceramic Company, Kyoto, Japan), which is a cementless ceramic-on-polyethylene design with ceramic tibial and femoral components and a polyethylene insert (C = ceramic; H = high-density polyethylene). This design is currently not available in the United States. (Courtesy of Tateishi H, Iwata Y, Futani H, et al: Clinical experience of ceramic cementless total knee arthroplasty in RA and a histologic study of the bone-ceramic interface in revision cases. *Bull Hosp Jt Dis* 1993;53:35-40.)

However, other investigators have reported an increased incidence of tibial component subsidence secondary to the increased rigidity of the ceramic implant.[24]

Bearing Surfaces for Other Joints

Ceramic materials have been utilized in bearing surfaces for shoulder and ankle arthroplasty as well as for arthroplasty in the hand.[25-27] The concern about brittle fracture and the reduced rate of polyethylene wear in the shoulder and hand as compared with the hip and knee have decreased interest in alternative bearing surfaces for these joints.

Summary

The reemergence of alternative bearing surfaces for total joint arthroplasty, after the initial success of metal-on-polyethylene bearings, has been largely spurred by findings of an association between polyethylene wear debris and periprosthetic osteolysis. Periprosthetic osteolysis is often seen in the younger, more active, higher-demand patient. Alternative bearing surfaces, with lower wear rates, can potentially improve the longevity of implant survival for the higher-demand patient by decreasing particulate debris formation and the resultant osteolysis. Patients who are older and less active will continue to be well served by metal-on-polyethylene bearings, because such bearings will undergo less cycling and thus be subject to less wear.

As new advances in prosthesis design and material properties have occurred over the past 30 years, the problems of particulate debris (primarily generated at the femoral head–polyethylene articulation) and periprosthetic osteolysis and aseptic loosening have become the subjects of intense clinical and laboratory research. Alternative bearing surfaces have the potential to be the next major breakthrough in thwarting these problems and increasing implant longevity, especially in younger, more active patients.

Some devices discussed in this article have not been cleared by the US Food and Drug Administration (FDA) or have been cleared by the FDA for specific purposes only. The FDA has stated that it is the responsibility of the physician to determine the FDA clearance status of each drug or device he or she wishes to use in clinical practice and to use the product with appropriate patient consent and in compliance with applicable law. Furthermore, any statements about commercial products are solely the opinions of the authors and do not represent Academy endorsement or evaluation of these products. Author statements in this journal may not be used in advertising or for any commercial purpose.

References

1. Black J: Prospects for alternate bearing surfaces in total replacement arthroplasty of the hip, in Puhl W (ed): *Performance of the Wear Couple BIOLOX Forte in Hip Arthroplasty: Proceedings of the 2nd Symposium on Ceramic Wear Couple*. Stuttgart, Germany: Ferdinand Enke Verlag, 1997, pp 2-10.
2. Harris WH: The problem is osteolysis. *Clin Orthop* 1995;311:46-53.
3. Ranawat CS, Peters LE, Umlas ME: Fixation of the acetabular component: The case for cement. *Clin Orthop* 1997; 344:207-215.
4. Jacobs JJ, Shanbhag A, Glant TT, Black J, Galante JO: Wear debris in total joint replacements. *J Am Acad Orthop Surg* 1994;2:212-220.

5. Walter A: On the material and the tribology of alumina-alumina couplings for hip joint prostheses. *Clin Orthop* 1992;282:31-46.
6. Müller ME: The benefits of metal-on-metal total hip replacements. *Clin Orthop* 1995;311:54-59.
7. Cuckler JM, Bearcroft J, Asgian CM: Femoral head technologies to reduce polyethylene wear in total hip arthroplasty. *Clin Orthop* 1995;317:57-63.
8. Fritsch EW, Gleitz M: Ceramic femoral head fractures in total hip arthroplasty. *Clin Orthop* 1996;328:129-136.
9. Simon JA, Dayan AJ, Ergas E, Stuchin SA, DiCesare PE: Catastrophic failure of the acetabular component in a ceramic-polyethylene bearing total hip arthroplasty. *J Arthroplasty* 1998;13: 108-113.
10. Dorlot JM: Long-term effects of alumina components in total hip prostheses. *Clin Orthop* 1992;282:47-52.
11. Mittelmeier H, Heisel J: Sixteen-years' experience with ceramic hip prostheses. *Clin Orthop* 1992;282:64-72.
12. Dalla Pria P: Recent innovations relating to the use of ceramic-ceramic hip joint prostheses, in Puhl W (ed): *Performance of the Wear Couple BIOLOX in Hip Arthroplasty: Proceedings of the 1st Symposium on Ceramic Wear Couple.* Stuttgart, Germany: Ferdinand Enke Verlag, 1996, pp 84-91.
13. Bonicoli F, Rughini L, Lunati PP, Di Puccio G, Secone S, Bonicoli E: Ceramic insert in uncemented press-fit titanium total hip prostheses: Our clinical experience in fifty-nine cases, in Puhl W (ed): *Performance of the Wear Couple BIOLOX Forte in Hip Arthroplasty: Proceedings of the 2nd Symposium on Ceramic Wear Couple.* Stuttgart, Germany: Ferdinand Enke Verlag, 1997, pp 38-42.
14. Rueda D, Álvarez M, Barahona F, Gómez Canedo J: Ceramic inserts in metal cups: A five-year experience, in Puhl W (ed): *Performance of the Wear Couple BIOLOX Forte in Hip Arthroplasty: Proceedings of the 2nd Symposium on Ceramic Wear Couple.* Stuttgart, Germany: Ferdinand Enke Verlag, 1997, pp 43-49.
15. Ravasi F, Portinaro N: Preliminary report on a new coupling system for alumina-alumina total hip replacement, in Puhl W (ed): *Performance of the Wear Couple BIOLOX in Hip Arthroplasty: Proceedings of the 1st Symposium on Ceramic Wear Couple.* Stuttgart, Germany: Ferdinand Enke Verlag, 1996, pp 55-58.
16. Weber BG: Experience with the Metasul total hip bearing system. *Clin Orthop* 1996;329(suppl):S69-S77.
17. Dorr LD, Hilton KR, Wan Z, Markovich GD, Bloebaum R: Modern metal on metal articulation for total hip replacements. *Clin Orthop* 1996;333: 108-117.
18. Wagner M, Wagner H: Preliminary results of uncemented metal on metal stemmed and resurfacing hip replacement arthroplasty. *Clin Orthop* 1996;329(suppl):S78-S88.
19. McKellop H, Park SH, Chiesa R, et al: In vivo wear of 3 types of metal on metal hip prostheses during 2 decades of use. *Clin Orthop* 1996;329(suppl): S128-S140.
20. Visuri T, Pukkala E, Paavolainen P, Pulkkinen P, Riska EB: Cancer risk after metal on metal and polyethylene on metal total hip arthroplasty. *Clin Orthop* 1996;329(suppl):S280-S289.
21. Amstutz HC, Grigoris P: Metal on metal bearings in hip arthroplasty. *Clin Orthop* 1996;329(suppl):S11-S34.
22. Yasuda K, Miyagi N, Kaneda K: Low friction total knee arthroplasty with the alumina ceramic condylar prosthesis. *Bull Hosp Jt Dis* 1993;53:15-21.
23. White SE, Whiteside LA, McCarthy DS, Anthony M, Poggie RA: Simulated knee wear with cobalt chromium and oxidized zirconium knee femoral components. *Clin Orthop* 1994;309:176-184.
24. Oonishi H, Aono M, Murata N, Kushitani S: Alumina versus polyethylene in total knee arthroplasty. *Clin Orthop* 1992;282:95-104.
25. Takakura Y, Tanaka Y, Sugimoto K, Tamai S, Masuhara K: Ankle arthroplasty: A comparative study of cemented metal and uncemented ceramic prostheses. *Clin Orthop* 1990;252:209-216.
26. Sim FH, Chao EYS, Pritchard DJ, Salzer M: Replacement of the proximal humerus with a ceramic prosthesis: A preliminary report. *Clin Orthop* 1980;146:161-174.
27. Minami M, Yamazaki J, Kato S, Ishii S: Alumina ceramic prosthesis arthroplasty of the metacarpophalangeal joint in the rheumatoid hand: A 2–4-year follow-up study. *J Arthroplasty* 1988;3:157-166.