Expert Reviews

State of the art in hard-on-hard bearings: how did we get here and what have we achieved?

Expert Rev. Med. Devices 8(2), 187–207 (2011)

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Total hip arthroplasty has shown excellent results in decreasing pain and improving function in patients with degenerative disease of the hip. Improvements in prosthetic materials, designs and implant fixation have now resulted in wear of the bearing surface being the limitation of this technology, and a number of hard-on-hard couples have been introduced to address this concern. The purpose of this article is to review the origins, development, survival rates and potential advantages and disadvantages of the following hard-on-hard bearings for total hip arthroplasty: metal-on-metal standard total hip arthroplasty; metal-on-metal hip resurfacing arthroplasty, ceramic-on-ceramic total hip arthroplasty; and ceramic-on-metal bearings. Improvements in the manufacturing of metal-on-metal bearings over the past 50 years have resulted in implants that provide low wear rates and allow for the use of large femoral heads. However, concerns remain regarding elevated serum metal ion levels, potential teratogenic effects and potentially devastating adverse local tissue reactions, whose incidence and pathogenesis remains unclear. Modern total hip resurfacing has shown excellent outcomes over 10 years in the hands of experienced surgeons. Current ceramic-on-ceramic bearings have demonstrated excellent survival with exceptionally low wear rates and virtually no local adverse effects. Concerns remain for insertional chipping, *in vivo* fracture and the variable incidence of squeaking. Contemporary ceramic-on-metal interfaces are in the early stages of clinical use, with little data reported to date. Hard-on-hard bearings for total hip arthroplasty have improved dramatically over the past 50 years. As bearing designs continue to improve with new and modified materials and improved manufacturing techniques, it is likely that the use of hard-on-hard bearings will continue to increase, especially in young and active patients.

Keywords: alumina • ceramic-on-ceramic • ceramic-on-metal • cross-linked polyethylene • hip resurfacing • metal-on-metal • pseudotumor • total hip arthroplasty

Since its introduction approximately 50 years ago, contemporary total hip arthroplasty has been shown to be reliably effective at reducing pain and improving function at follow-up times of a decade or more in the large majority of patients. Initially, this procedure was primarily intended for use in older, low-demand patients with end-stage degenerative joint disease, with the goal of reducing disease-related pain and affording sufficient mobility for activities of daily living. However, the life expectancy in developed countries continues to increase, and many patients with degenerative hip disease wish to maintain high activity levels well into older age [1]. In addition, the use of hip arthroplasty in young patients has been increasing [301], and this population typically places higher demands and stresses onto orthopedic implants, while also having several decades of life expectancy remaining. As a result, total hip arthroplasty is frequently being used in patients who expect to maintain highly active lifestyles for decades following the procedure [2–4].

Historically, the dominant bearing surface in total hip arthroplasty was a metal head articulating with a polyethylene acetabular component. Initially, implant loosening due to any of a number of factors, such as implant fracture, failure of cement fixation, osteolysis or stress shielding, was the primary mode of failure with hip

 10.1586/ERD.10.75 ISSN 1743-4440

arthroplasty prostheses [5]. However, improvements in prosthetic materials, implant designs and methods of fixation led to bearing materials being a major limitation of this technology. Ever since associations were described between higher activity levels, increased polyethylene wear rates, polyethylene debris and early implant failure due to aseptic loosening [6–8], renewed efforts have been made to develop more advanced bearings to both decrease wear rates and reduce bearing dislocation rates. In general, these efforts can be categorized into one of two groups: modification of the traditional metal-on-polyethylene bearings; and the development of alternative hard-on-hard interfaces. Highly cross-linked polyethylene, manufactured by γ-irradiation of the base material, has increased in popularity substantially over the past decade. In 2008, cross-linked polyethylene was used in approximately 75% of hip replacements performed in the USA, more than ten-times the number of cases performed using standard polyethylene [9]. While cross-linking of polyethylene has been demonstrated to reduce wear rates [10,11], concerns remain regarding decreased resistance to fatigue following irradiation, despite anti-oxidation strategies, such as serial melting or doping with vitamin E [12–14]. The second approach has involved the development of bearing couples with hard materials, such as metal and ceramic, that promised to increase implant longevity through improved tribology (more uniform lubrication and decreased friction), lower dislocation rates and decreased wear.

The purpose of this article is to review the origins, development, survival rates and potential advantages and disadvantages of the following hard-on-hard bearings for total hip arthroplasty:

- Metal-on-metal standard total hip arthroplasty;
- Metal-on-metal hip resurfacing arthroplasty;
- Ceramic-on-ceramic total hip arthroplasty;
- Ceramic-on-metal bearings.

Search strategy

A thorough search was performed of the PubMed and EMBASE databases to identify all relevant articles using combinations of the following keywords: metal-on-metal, ceramic-on-ceramic, ceramic, alumina, hip arthroplasty, hip resurfacing and hip replacement. Any articles that reported either *in vitro* or *in vivo* results of, or complications with, the use of metal-on-metal, ceramic-on-ceramic or ceramic-on-metal bearings for hip arthroplasty, as well as review articles addressing these topics, were retrieved and reviewed. Only English language articles, or those with English abstracts were included. Any reports of studies that evaluated revision hip arthroplasties, or that included fewer than 20 hips, were excluded. The reference lists of all relevant manuscripts were referenced against the list of those retrieved from the database search, and any that were not present were sourced and retrieved for review. Primary source articles were grouped by the type of bearing interface addressed, and the following data were extracted to a spreadsheet for each *in vivo* study: the number of hips studied, follow-up times, the type of implant and bearing, including method of fixation, survival rates, the incidence and type of complications, and wear rates if reported. For all *in vitro* studies, the data extracted included: the number and type of bearings studied, the experimental methodology used and the reported findings, including wear rates. The extracted data were then systematically reviewed and summarized. In addition, the potential advantages of decreased wear, decreased osteolysis and lower incidence of dislocation were assessed for each bearing couple. The reported complications were reviewed to identify any potential disadvantages related to the individual interfaces.

Metal-on-metal standard total hip arthroplasty

Origins, development & results

Metal-on-metal total hip arthroplasty prostheses were reported as early as the 1930s, but the first modern stemmed femoral designs appeared around 1960, at approximately the same time as metal-on-polyethylene articulations. In 1966, McKee and Watson-Farrar reported that 94% of the first 50 patients treated with their prosthesis had no pain and ambulated with minimal or no limp at follow-up times of 2–4 years [15], and design improvements were made based on this initial experience in an attempt to further improve the outcomes with this implant [16,17]. However, there were concerns that these first-generation metal-on-metal prostheses had a higher rate of aseptic loosening than the Charnley metal-on-polyethylene implants and despite the incomplete understanding of the mechanisms of failure, these bearings were largely abandoned by the mid-1970s [18–20]. Nevertheless, some investigators have reported good long-term survival rates for these first-generation devices ranging from 74 to 85% at follow-up times from 20 to 28 years [21,22]. An overview of selected survival rates of early and contemporary metal-on-metal total hip arthroplasty can be found in Table 1.

Some authors have suggested that limitations in manufacturing technology may have resulted in inconsistent and suboptimal dimensions of these early-generation metal-on-metal prostheses [23–25], leading to excessive friction, seizing and implant loosening. While the importance of consistent component sphericity and avoidance of equatorial articulation (a condition where the acetabular inner diameter is smaller than the outer diameter of the femoral head, leading to loading of the rim-head interface, see Figure 1) have been demonstrated in *in vitro* studies, neither of these phenomena have been consistently demonstrated in an analysis of explanted failed implants [26]. However, some retrieval studies revealed signs of impingement between the femoral neck and acetabular rim. Walker *et al.* reported impingement abrasion in a case report of a retrieved femoral stem [27]; Willert *et al.* reported impingement abrasion in two of eight retrieved femoral stems [28]; and Howie *et al.* reported impingement damage in nine of 24 retrieved McKee–Farrar stems [29]. These reports suggested that component design issues, such as inadequate offset of the head, and/or an excessively thick or poorly positioned neck, perhaps exacerbated by malpositioning of the acetabular cup, may have been responsible for the higher failure rates reported with these components.

In the late 1980s to early 1990s, a second generation of metal-on-metal devices was introduced in an attempt to reduce the substantial incidence of osteolysis and aseptic loosening associated

Table 1. Reported survival rates of first- and second-generation metal-on-metal total hip arthroplasty.

Study (year)	Number of hips (patients)	Type of bearing design	Mean follow-up in months (range)	Femoral fixation	Acetabular fixation	Survival (%)	Ref.
First-generation stemmed total hip arthroplasty							
Brown *et al.* (2002)	123 (101)	Modified low-tolerance CoCrMo	336	Cemented	Cemented	74†	[21]
Gerritsma-Bleeker *et al.* (2000)	146 (135)	Modified low-tolerance CoCrMo	264	Cemented	Cemented	85†	[22]
Higuchi *et al.* (1997)	38 (38)	Modified low-tolerance CoCrMo	135 (24–240)	Cemented	Cemented	71	[20]
August *et al.* (1986)	657 (NR)	Modified low-tolerance CoCrMo	240	Cemented	Cemented	28†	[19]
Dandy *et al.* (1975)	739 (NR)	Modified low-tolerance CoCrMo	60 (24–96)	Cemented	Cemented	93	[16]
McKee and Farrar (1966)	50 (50)	Low-tolerance CoCrMo	36 (24–48)	Cemented	Cemented	96	[15]
Second-generation stemmed total hip arthroplasty							
Berton *et al.* (2010)	100 (92)	High-tolerance CoCrMo	43 (24–58)	Uncemented	Uncemented	92	[34]
Long *et al.* (2010)	207 (181)	High-tolerance CoCrMo	19 (12–24)	Uncemented	Uncemented	85	[35]
Neumann *et al.* (2009)	100 (99)	High-tolerance CoCrMo	126 (120–143)	Uncemented	Uncemented	94	[251]
Paleochorlidis *et al.* (2009)	99 (84)	High-tolerance CoCrMo	9.5 years (6–15 years)	Uncemented	Uncemented	95	[51]
Zijlstra *et al.* (2009)	102 (NR)	High-tolerance CoCrMo	60	Cemented	Cemented	97†	[48]
Dastane *et al.* (2008)	82 (80)	High-tolerance CoCrMo	66 (26–140)	Uncemented	Uncemented	99	[43]
Delaunay *et al.* (2008)	83 (73)	High-tolerance CoCrMo	120	Uncemented	Uncemented	96†	[44]
Eswaramoorthy *et al.* (2008)	85 (82)	High-tolerance CoCrMo	132 (120–144)	Uncemented	Cemented	96	[37]
Grubl *et al.* (2007)	105 (98)	High-tolerance CoCrMo	120	Uncemented	Uncemented	99†	[42]
Sharma *et al.* (2007)	209	High-tolerance CoCrMo	72 (60–132)	Cemented	Cemented	95	[40]
Milosev *et al.* (2006)	640 (591)	High-tolerance CoCrMo	120	Uncemented	Uncemented	92†	[47]
Saito *et al.* (2006)	106 (90)	High-tolerance CoCrMo	72 (60–96)	Uncemented	Cemented	99	[39]
Jacobs *et al.* (2004)	95 (95)	High-tolerance CoCrMo	40 (36–68)	Uncemented	Uncemented	99	[45]
Long *et al.* (2004)	161 (154)	High-tolerance CoCrMo	76 (24–108)	Uncemented	Uncemented	96	[38]
MacDonald *et al.* (2003)	22 (22)	High-tolerance CoCrMo	38 (26–47)	Uncemented	Uncemented	100	[252]
Lombardi *et al.* (2001)	78 (78)	High-tolerance CoCrMo	39 (23–62)	Uncemented	Uncemented	100	[46]
Dorr *et al.* (2000)	70 (70)	High-tolerance CoCrMo	60 (48–84)	Uncemented	Uncemented	98	[36]
Wagner *et al.* (2000)	76 (76)	High-tolerance CoCrMo	60 (44–88)	Uncemented	Uncemented	100	[41]
Wagner *et al.* (1996)	70	High-tolerance CoCrMo	34 (24–61)	Uncemented	Uncemented	100	[49]
Weber *et al.* (1996)	100 (98)	High-tolerance CoCrMo	48 (24–84)	Uncemented	Uncemented	95	[33]

†Survivorship at noted follow-up time.
CoCrMo: Cobalt–chromium–molybdenum; NR: Not reported.

with long-term follow-up of the commonly used metal-on-polyethylene implant designs. The importance of consistent and accurate head-cup clearance has been recognized as an important contributor to wear in large-diameter metal-on-metal bearings. While low bearing clearance is beneficial in terms of reducing wear rates, and increasing clearance from 100 µm by as little

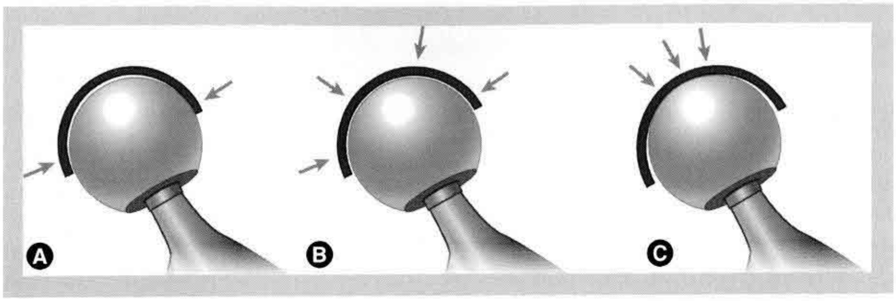

Figure 1. Principal points of loading in (A) equatorial, (B) total contact and (C) polar bearings.

as 50 µm has been reported to markedly increase wear [30,31], deformation of thin monoblock cups at the time of implantation can reduce clearance at the rim [32], potentially resulting in catastrophic edge loading if not accounted for in the implant design. Innovations in metallurgy allowed for the use of harder metal alloys for articulating surfaces, and advances in machining technology ensured consistently accurate component interface dimensions with tighter manufacturing tolerances [33]. It was hoped that these advances, along with new component designs that incorporated improved stem fixation and narrower, higher offset femoral necks, would provide low component friction, minimal wear and excellent range of motion, resulting in improved implant survivorship. The Metasul® bearing (Sulzer Ltd, Winterthur, Switzerland) was among the first of the second-generation metal-on-metal prostheses, introduced into clinical use in 1988, and in 1996 Weber reported 95% survival of the first 110 cemented total hip arthroplasties performed using this interface at a mean follow-up of 4 years (range: 2–7 years) [33]. Recently, high early failure rates have been reported for one specific implant design, with Long *et al.* and Berton *et al.* reporting survival rates of 85% at a mean follow-up of 19 months and 92% at a mean follow-up of 43 months, respectively [34,35]. However, many authors have reported survival rates ranging from 92 to 100% at follow-up times ranging from 4 to 12 years [36–51] with other contemporary metal-on-metal implants, suggesting that the higher early failure rates of first-generation metal-on-metal implants have been addressed by new-generation bearings.

Potential benefits of metal-on-metal articulations

Metal-on-metal total hip arthroplasty provides the principal benefit of potentially reduced wear compared with older polyethylene articulations. After an initial run-in period over the first 1–2 years, during which time linear wear rates of 20–25 µm/year have been reported, a low steady-state linear wear rate of 2.5–10 µm/year is usually achieved [25,52,53]. This translates into a 20–180-times lower linear wear rate compared with conventional metal-on-polyethylene bearings [25,54], although because of the considerably smaller mean size of metal wear particles, the number of wear fragments is typically greater [55,56]. Even with modern metal-on-metal bearings, there is considerable heterogeneity in metallurgical properties, with variability in alloy composition and manufacturing techniques. Both *in vitro* and *in vivo* studies have suggested that there may be considerable differences in material wear and implant failure rates based on whether implants are manufactured using a wrought, cast or heated-cast process, although the published results are contradictory [47,57–60]. However, several authors have reported improved wear characteristics and survival rates of high carbon versus low carbon cobalt–chromium alloys in metal-on-metal hip resurfacing arthroplasties [54,56,61,62]. The commercial introduction of highly cross-linked polyethylene has reduced wear rates, with one *in vitro* study reporting volumetric wear rates of 3 mm^3 per million cycles compared with 48 mm^3 per million cycles before cross-linking [11]. Nevertheless, these rates remain markedly higher than the steady state volumetric wear rates of between 0.06 and 0.11 mm^3 per million cycles observed during *in vitro* testing of metal-on-metal bearings manufactured from three different cobalt–chromium alloys [61]. In addition, the articulation of metal-on-metal bearings has a self-polishing function, which can remove any surface scratches caused by third body particulate wear [63]. This ensures that the interface remains smooth, minimizing bearing friction and the generation of wear particles, and improving longevity of the implant.

Besides lower volumetric and linear wear rates, metal-on-metal bearings afford the ability to use larger diameter femoral head sizes than traditional articulations. Many contemporary metal-on-metal implant designs include a thin monoblock acetabular component, typically resulting in a difference of between 6 and 8 mm between the femoral and acetabular component outer diameters. This allows for the use of a near-anatomic-sized prosthetic femoral head. With other interfaces, such as metal-on-polyethylene or ceramic-on-ceramic, the acetabular component consists of an outer metal shell, as well as a polyethylene or ceramic insert. Even with the newest thin cross-linked polyethylene, a minimum liner thickness of several millimeters is necessary in addition to the metal cup to ensure adequate fracture and wear resistance, resulting in an increased total wall thickness of the acetabular component and consequently a smaller maximal femoral head size. D'Antonio *et al.* recently reported restoring the femoral head size to within 6 mm of the anatomic diameter in a blinded study of 89 total hip arthroplasties performed using a monoblock shell metal-on-metal total hip arthroplasty design [64]. Increased femoral head size has been historically associated with increased volumetric wear in metal-on-polyethylene articulations, based on the work of Livermore *et al.* who reported significantly higher volumetric wear rates of 32-mm heads compared with 22- and 28-mm components [65]. However, larger femoral head sizes in metal-on-metal articulations are associated with a shorter bedding-in period and decreased volumetric wear during this time [31]. This difference has been attributed to improved lubrication with larger femoral head diameters. Smith *et al.* reported that 36-mm heads exhibited bearing surface separation during most of a simulated *in vitro* gait cycle, compared with smaller head sizes of between 16 and 28 mm that showed little to no separation [66]. In addition, similar wear rates have been reported in biomechanical studies independent of component size once a steady state period is reached, typically following 1–2 million cycles [55,67].

The use of a larger femoral head diameter improves joint stability by increasing the minimum head displacement necessary for dislocation and increasing the range of motion prior to neck-cup impingement. To escape the prosthetic articulation, the head must be displaced by a minimum of half of the femoral head diameter both distally and laterally relative to the acetabular cup. This is termed the jump distance, and is directly proportional to the femoral head size (Figure 2). Dislocation can occur as a result of impingement of the prosthetic neck against the rim of the acetabular component, which acts as a fulcrum to lever the femoral head out of the cup. As the femoral head to neck ratio increases, there is a concurrent increase in the range of motion of the prosthetic joint prior to dislocation (Figure 3) [68–70]. Because of these two phenomena, the use of larger femoral head sizes has been demonstrated to improve joint stability and reduce the incidence of dislocations as demonstrated clinically in a number of studies [70–76]. Furthermore, some authors have suggested that lubricated metal-on-metal bearings have an adhesive force between surfaces that imparts a suction fit unique to this bearing combination, further stabilizing the prosthetic interface and reducing the risk of dislocation [77,78].

Metal-on-metal bearings provide an additional potential advantage of minimizing periprosthetic osteolysis. While Holloway *et al.* reported a 23% incidence of peri-acetabular osteolysis in 29 polyethylene sandwich cup metal-on-metal total hip arthroplasties at a mean follow-up of 105 months (range: 26–128 months) [79], several authors have reported incidences of osteolysis with similar implants of between 0 and 3% at mean follow-up times ranging from 60 to 85 months [36,41,80–83]. In a prospective, randomized comparison of 39 metal-on-metal and 39 metal-on-conventional-polyethylene total hip arthroplasties, Migaud *et al.* reported a significantly higher incidence of osteolysis in the polyethylene group (9 vs 0 hips; $p = 0.004$) at a mean follow-up of 69 months (range: 61–80 months) [83]. This suggests that metal-on-metal articulations do provide the benefit of extremely low rates of osteolysis, which may be further reduced with the use of monoblock acetabular components that completely eliminate the use of polyethylene.

Metal-on-metal articulations may provide an additional benefit in allowing the use of a hard-on-hard articulation in patients requiring acetabular reconstruction with a cup-cage construct. Although uncommon, metal-on-metal articulations have been utilized in young patients with severe deformity requiring acetabular reconstruction with good mid-term results. Girard *et al.* reported on a series of 23 total hip arthroplasties performed in 22 patients who had a mean age of 44 years (range: 24–56 years) at the time of surgery [84]. All patients had severe acetabular bone loss that prevented the use of press-fit acetabular components, and consequently had a Metasul® (Zimmer-Centerpulse, Winterhur, Switzerland) cup cemented into a metal reinforcement ring. At a mean follow-up of 6 years (range: 5–10 years), the mean Harris Hip Score was 95 points (range: 84–100), and there was one revision (96% survival) for aseptic loosening. To the best of the authors' knowledge, no similar results have been reported with other hard-on-hard bearing combinations.

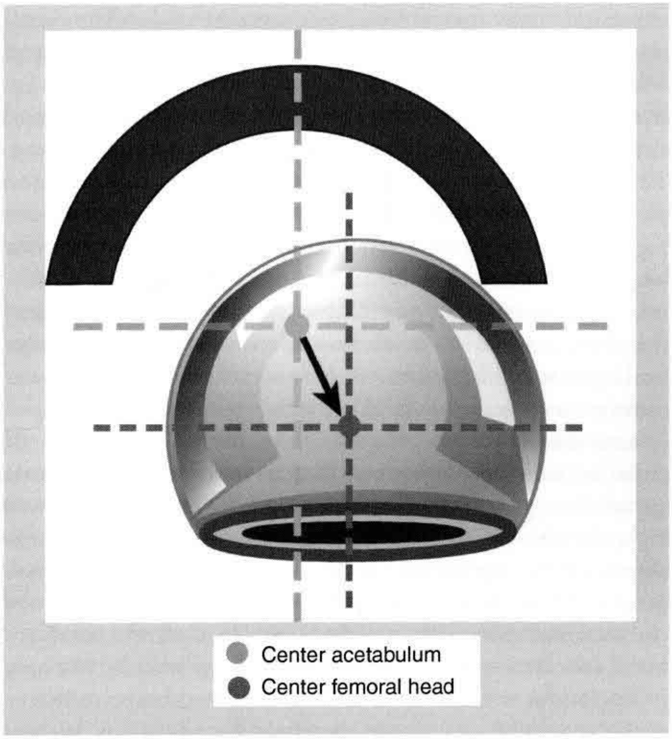

Figure 2. The jump distance required for dislocation is proportional to the radius of the femoral head.

Potential disadvantages & complications

The advantages of this bearing surface must be balanced against the possible adverse effects of particulate metal debris. Although the total volume of the metallic debris is lower than with conventional polyethylene, the mean particulate size is much smaller. Hence, it is estimated that the total number of metallic particles is anywhere from 13- to 1000-times the number of polyethylene particles produced with conventional polyethylene bearing surfaces [55,56,85]. A number of authors have documented significantly increased serum concentrations of both cobalt and

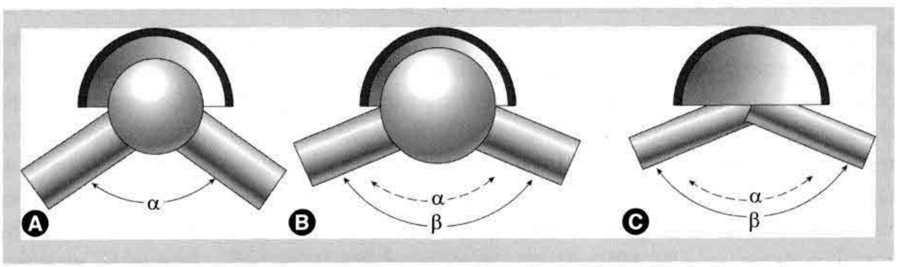

Figure 3. Maximum range of motion prior to neck impingement (A) is related to the head-neck ratio, which increases with the use of a larger femoral head (B), or thinner femoral neck (C).

chromium ions compared with patients who underwent metal-on-polyethylene total hip arthroplasty, as well as control subjects who had not undergone prosthetic implantation [86–89]. Serum ion levels have been reported to peak within 12 months of implantation of a metal-on-metal prosthesis and then begin to decrease. This is consistent with higher wear during the initial bedding-in period [90,91]. Some authors have identified an association between high acetabular cup inclination angles and elevated serum ion levels [92,93], although other investigators have failed to consistently demonstrate this relationship [94,95]. It has been suggested that these increased ion levels may be caused by component edge loading [93,95], which is most likely to occur with steep acetabular inclination angles in conjunction with smaller component sizes.

Some theoretical concerns continue to be voiced regarding the potential teratogenic effects of the elevated local and systemic ion levels in patients who have undergone metal-on-metal total hip arthroplasty. Cobalt and chromium wear particles have been demonstrated to promote carcinoma in animals [96], and cytogenetic studies have revealed a significantly higher incidence of chromosomal aberrations in patients with an implanted metal-on-metal articulation when compared with those who did not have an implant or who had been revised to a metal-on-polyethylene articulation [97,98]. However, the clinical implications of these findings remain unclear and no evident association has been shown between the use of these implants and neoplastic disease in humans. In the largest known reported epidemiological evaluation of the incidence of cancer cases in patients who had undergone metal-on-metal total hip arthroplasty, Visuri *et al.* compared the number of cancer cases in 579 Finnish patients who had undergone McKee–Farrar metal-on-metal total hip arthroplasty and had a total follow-up of 9092 person-years to the general population [99]. The authors found a similar incidence of all cancers between the two groups (standardized incidence ratio [SIR]: 0.95; 95% CI: 0.79–1.13), and a significantly lower incidence of lung cancer than expected over the follow-up period (SIR: 0.44; 95% CI: 0.18–0.91). The incidences of all other cancers were similar to the general population, although the observed increase in cases of leukemia in metal-on-metal patients approached significance (SIR: 2.31; 95% CI: 0.93–4.76). It is also worth noting that elevated ion levels are found in all patients with implanted arthroplasty prostheses as a result of corrosion, and Leutzner *et al.* reported that serum levels of cobalt, chromium and molybdenum levels were similar in patients with well-functioning metal-on-polyethylene total knee arthroplasties as compared with cementless metal-on-metal total hip arthroplasty [100]. While the present authors are not aware of any documented association between the presence of a metal-on-metal hip arthroplasty and complications during or after pregnancy, Ziaee *et al.* recently reported higher mean umbilical cord blood cobalt and chromium concentrations at the time of delivery in ten patients with implanted metal-on-metal articulations compared with ten control subjects without metal implants (cobalt 0.839 vs 0.341 μg/ml; $p < 0.01$; chromium 0.378 vs 0.199 μg/ml; $p > 0.05$) [101]. Because of the theoretical possibility of adverse effects on the fetus, many investigators believe that metal-on-metal bearings are relatively contraindicated in women of childbearing age [101–103]. However, despite half a century of clinical experience with metal-on-metal bearings for hip arthroplasty, to date there is no clear evidence of increased cancer incidence in patients who have received these implants.

Perhaps the most devastating potential complication of metal-on-metal bearings is the development of adverse local tissue reactions. Several authors have reported osteolysis, aseptic lymphocytic vasculitis-associated lesions (ALVAL), pseudotumors and soft-tissue destruction in patients who have received metal-on-metal hip implants [104–106]. These phenomena are believed to be a reaction to locally deposited metal wear particles, although in many cases, little metal debris is evident on microscopic evaluation of periprosthetic tissues, and only rarely are these reactions associated with macroscopic metallosis [105,107]. In addition, similar adverse local tissue reactions have been described in metal-on-polyethylene articulations [108]. The two most frequently-cited complications are aseptic lymphocytic vasculitis-associated lesions (ALVAL), which are histologically diagnosed lymphocytic infiltrations of local tissues typically resulting in their destruction and, by contrast, pseudotumors, which are typically radiologically diagnosed periprosthetic cystic or solid structures that are not necessarily symptomatic or destructive. Willert *et al.* reported that five patients with local inflammatory reactions following metal-on-metal total hip arthroplasty were revised to a new metal-on-metal prosthesis, but continued to experience hip and thigh pain [104]. Two of these patients underwent subsequent revision to a non-metal-on-metal prosthesis 4 months and 5 years following the first revision, with resolution of symptoms. Although the cause of these reactions remains unclear, some authors have implicated a delayed hypersensitivity reaction resulting in an autoimmune response to both the metal particles and the surrounding soft tissues. This is supported by a recent report from Thomas *et al.* who confirmed a systemic metal sensitivity by patch testing and lymphocyte transformation testing in 13 of 16 patients who underwent revision of a failed metal-on-metal total hip arthroplasty associated with periprosthetic lymphocytic inflammation [109]. It should be noted that the great majority of these adverse local tissue reactions (ALTRs) appear to be due to altered hip prosthetic mechanics. Specifically, they have been commonly associated with cup malpositioning (steep acetabular inclination angle or altered anteversion of the acetabular or femoral components). A range of results has been reported for the prevalence of ALTR following metal-on-metal hip arthroplasty, primarily resurfacing, ranging from less than 0.15 to 4% by 8 years of follow-up [110–114]. Glyn-Jones *et al.* suggested that a higher incidence of pseudotumor formation may be associated with resurfacing performed in women under the age of 40 years [110]. It appears that pseudotumor formation may additionally be associated with the use of larger diameter prosthetic heads, with only one case report in the literature in two patients with 28-mm heads [115]. However, the exact incidence of these reactions is unknown, and it remains unclear why a few centers in the UK appear to have a substantially higher reported rate of these complications. Although the ability to predict which patients will develop these reactions remains elusive, most experienced investigators recommend avoiding the use of metal-on-metal articulations in patients who have a documented metal allergy, such as a contact hypersensitivity to costume jewelry. The authors believe that any patients with an adverse local tissue reaction that requires revision should receive a nonmetal-on-metal bearing.

Summary

In summary, modern high-tolerance metal-on-metal total hip arthroplasty has been in clinical use for over a decade, and consistently excellent survivorship and clinical outcomes have been reported with its use. Recently, there has been some concern regarding higher failure rates for this bearing couple, but this appears to be the result of design issues with specific implant models. Many investigators have advocated the use of metal-on-metal bearings in young and active patients because of the potentially improved joint stability and gait parameters associated with large femoral head sizes, and the extremely low wear rates compared with both traditional and highly cross-linked polyethylene actetabular components. However, there has been a recent increase in concerns regarding adverse reactions to both local and systemic distribution of metal wear particles. While adverse local tissue reactions appear to be rare in most reports, they can be devastating, and the true incidence remains unknown. For this reason, a better understanding of the pathogenesis of these reactions is critical to avoiding the patient and/or surgical risk factors that may predispose to these reactions, and substantial research efforts are currently being directed to this end. In the interim, patients should be made aware of the risks associated with these bearings. Although there is limited evidence to suggest any teratogenic effects of metal-on-metal bearings or an increased risk of adverse reactions in patients with metal hypersensitivity, surgeons may wish to avoid the use of metal-on-metal bearings in women of childbearing age and patients with known sensitivity to costume jewelry.

Metal-on-metal total hip resurfacing

Origins, development & results

The first-generation metal-on-metal total hip resurfacing arthroplasties were developed in the 1960s by several surgeons, including Gerard, Müller and Boltzy [116,117]. However, the clinical results with these designs were found to be suboptimal. In the 1970s, total hip resurfacing was re-introduced with the use of metal-on-polyethylene articulations, as an attempt to provide an alternative to conventional total hip arthroplasties that were experiencing high rates of stem loosening. The design goals for these prostheses included minimizing femoral bone loss and anatomic positioning of the femoral and acetabular components. These early total hip resurfacing prostheses typically consisted of a stemless hemispherical femoral component articulating with a cemented polyethylene acetabular cup. Early results with these devices were promising, with investigators reporting survival rates of between 98 and 100% at follow-up times ranging from 4 months to 4 years [118–120]. However, a high incidence of component loosening attributed to polyethylene wear and osteolysis became apparent over longer follow-up periods, with 5-year survivorship reported between 70 and 77% [121,122], and dropping to 40% at 8 years for one design [122]. In addition, revision of failed first-generation resurfacings was complicated by poor acetabular bone stock secondary to the extensive reaming needed at the time of the primary procedure, compounded by wear-related osteolysis [118]. As a result of these shortcomings, these designs were largely abandoned in the 1980s, although a few investigators used a modified femoral resurfacing component for hemiarthroplasty procedures in selected young patients with osteonecrosis [123,124].

With the introduction of second-generation metal-on-metal bearings for total hip arthroplasty in the late 1980s, interest emerged in adapting these advances for hip resurfacing. It was hoped that the use of thin monoblock shells would allow for the preservation of bone stock by using smaller acetabular components, as well as avoiding the polyethylene wear and resulting osteolysis responsible for the high incidence of early component loosening with metal-on-polyethylene resurfacing designs [125,126]. Outcomes with the currently available implant designs over follow-up times approaching 10 years have recently been reported. Amstutz *et al.* reported a 92% survivorship at 8 years in the first 1000 consecutive metal-on-metal resurfacing arthroplasties implanted by the first author [127], and noted a reduction in the incidence of mechanical failure subsequent to surgical technique modifications made after the 300th procedure. In a multicenter study, Khan *et al.* reported a 96% survivorship at 8 years of 652 resurfacings performed by 58 different surgeons in eight countries, with a mean Harris Hip score of 91 points (range not reported) at a median follow-up time of 6 years (range: 5–8 years) [128]. A number of investigators have reported short- and medium-term outcomes with modern hip resurfacing [129–133]. Several additional prospective or consecutive series studies have revealed survival rates of between 95 and 97% at mean follow-up times of 5–7 years [113,134,135]. While the majority of results are very good, some authors have reported higher early failure rates with modern total hip resurfacing, ranging from 7% within 2 years of implantation to 30% at a mean follow-up of 9 years following surgery [58,136–139]. This variability of results might be due to the technically challenging nature of the procedure associated with a substantial learning curve [136,137,140–142], which has the potential for high failure rates if performed without sufficient training, or by inexperienced surgeons. In addition, some authors have suggested that early failure may in some cases be the result of bone necrosis at the time of femoral component cementing, resulting in failure of cement fixation [143,144]. While some authors have recommended the use of various surgical technique modifications to reduce maximum bone temperatures during cement curing [145,146], recently, cementless fixation of femoral components for hip resurfacing has been introduced and may overcome this potential mode of failure [139]. A review of reported outcomes with contemporary metal-on-metal hip resurfacing arthroplasty can be found in Table 2.

Potential advantages of resurfacing

Because of the similarity of the bearing surfaces, metal-on-metal resurfacing has many of the same advantages as metal-on-metal total hip arthroplasty, including: reduced wear; the ability to

Table 2. Reported survival rates of contemporary metal-on-metal hip resurfacing arthroplasty.

Study (year)	Number of hips (patients)	Type of bearing design	Mean follow-up in months (range)	Femoral fixation	Acetabular fixation	Survival (%)	Ref.
Daniel *et al.* (2010)	184 (160)	CoCrMo resurfacing	84 (24–130)	Cemented	Uncemented	84	[58]
Madhu *et al.* (2010)	117 (101)	CoCrMo resurfacing	84 (60–113)	Cemented	Uncemented	93	[253]
Vendittoli *et al.* (2010)	109 (NR)	CoCrMo resurfacing	56 (36–72)	Cemented	Uncemented	94	[132]
Bergeron *et al.* (2009)	228 (209)	CoCrMo resurfacing	55	Cemented	Uncemented	97†	[134]
Killampalli *et al.* (2009)	100 (100)	CoCrMo resurfacing	NR (2–5 years)	Cemented	Uncemented	100	[254]
Mont *et al.* (2009)	54 (54)	CoCrMo resurfacing	40 (24–60)	Cemented	Uncemented	96	[255]
Ollivere *et al.* (2010)	104 (94)	CoCrMo resurfacing	61 (38–76)	Cemented	Uncemented	100	[256]
Zywiel *et al.* (2009)	33 (33)	CoCrMo resurfacing	45 (24–67)	Cemented	Uncemented	100	[133]
Amstuz *et al.* (2008)	1000 (838)	CoCrMo resurfacing	68 (13–133)	Cemented	Uncemented	95	[127]
Falez *et al.* (2008)	60 (58)	CoCrMo resurfacing	32 (2–44)	Cemented	Uncemented	92	[257]
Gross and Liu (2008)	17 (17)	CoCrMo resurfacing	89 (64–100)	Uncemented	Uncemented	85	[139]
Heilpern *et al.* (2008)	110 (98)	CoCrMo resurfacing	71 (60–93)	Cemented	Uncemented	96	[135]
Kim *et al.* (2008)	200 (200)	CoCrMo resurfacing	31 (12–54)	Cemented	Uncemented	93	[136]
McGrath *et al.* (2008)	40 (35)	CoCrMo resurfacing	36 (24–72)	Cemented	Uncemented	95	[258]
Steffen *et al.* (2008)	610 (532)	CoCrMo resurfacing	60 (24–96)	Cemented	Uncemented	95	[113]
Marker *et al.* (2007)	550 (NR)	CoCrMo resurfacing	44 (7–75)	Cemented	Uncemented	93	[137]
Mont *et al.* (2007)	614 (724)	CoCrMo resurfacing	33 (24–60)	Cemented	Uncemented	98	[165]
Nishii *et al.* (2007)	50 (45)	CoCrMo resurfacing	5 years	Cemented	Uncemented	96†	[259]
Pollard *et al.* (2006)	63 (NR)	CoCrMo resurfacing	61 (52–71)	Cemented	Uncemented	94	[260]
Vail *et al.* (2006)	57 (52)	CoCrMo resurfacing	36 (24–48)	Cemented	Uncemented	97	[131]
Lilikakis *et al.* (2005)	70 (66)	CoCrMo resurfacing	29 (24–38)	Uncemented	Uncemented	97	[261]
Treacy *et al.* (2005)	144 (130)	CoCrMo resurfacing	60	Cemented	Uncemented	98†	[262]
Daniel *et al.* (2004)	446 (384)	CoCrMo resurfacing	39 (24–98)	Cemented	Uncemented	99	[129]

†Survivorship at noted follow-up time.
CoCrMo: Cobalt–chromium–molybdenum; NR: Not reported.

use larger femoral heads improving stability and decreasing the number of dislocations; and a reduced incidence of osteolysis. Resurfacing has the additional unique advantage of preserving femoral bone stock when compared with conventional stemmed total hip arthroplasty, without requiring additional resection of acetabular bone [147]. This allows for an eventual revision to a primary total hip implant should the bearing fail, which is particularly advantageous in young and highly active patients who have several decades of remaining life expectancy and can be expected to outlive any of the currently available hip prostheses. However, while the revision of a failed resurfacing femoral component is typically straightforward and similar in complexity to a primary total hip arthroplasty [148,149], some authors have noted that the procedure can be more technically demanding should the acetabular cup need to be replaced [150].

Metal-on-metal hip resurfacing may additionally provide benefits in terms of restoration of native joint biomechanics and limb length. In one gait study, Mont *et al.* found significantly more natural abductor and extensor moments and better walking speed in 15 patients following hip resurfacing arthroplasty when compared with 15 patients who underwent standard total hip arthroplasty and 10 patients with osteoarthritis of the hip [151]. Nantel *et al.* reported that abductor and extensor moments were significantly closer to disease-free hips following resurfacing as compared with large femoral head metal-on-metal total hip arthroplasty [152], suggesting that this benefit is unique to resurfacing and not a result of the larger femoral head size. However, the significance of these findings remains unclear as a prospective randomized study of 48 patients from the same center as the report by Nantel *et al.* revealed no differences between resurfacing and large femoral head total hip arthroplasty in terms of functional tests, including the timed up and go test, hop test and flexor and abductor strength ratio test, or clinical outcomes, including Western Ontario and McMaster Universities score (WOMAC), 12-item Short-Form Health Survey (SF-12) and University of California Los Angeles (UCLA) activity scores [153]. However, irrespective of gait mechanics, Girard *et al.* have reported that hip resurfacing arthroplasty restores leg length inequality in a greater proportion of patients when compared with standard total hip arthroplasty [154].

Potential disadvantages

Resurfacing has several unique potential disadvantages in addition to those inherent to all metal-on-metal bearings. Perhaps most concerning is the risk of femoral neck fracture, which several authors have reported to be most pronounced in the early part of the learning curve [137,155,156]. While sufficient training under an experienced resurfacing surgeon, avoiding patients with smaller femoral necks and/or poorer quality bone, and meticulous surgical technique and implant positioning can reduce the incidence of this complication to below 1% [127,129,137], it nevertheless remains a devastating complication that is unique to hip resurfacing. In addition, because the native head-neck junction is preserved with this procedure, there is a limited ability to modify femoral offset at the time of surgery. This is particularly relevant when patients have advanced degenerative changes of the hip with marked femoral head collapse or bone loss. Several authors have reported decreased mean horizontal offsets following hip resurfacing arthroplasty of between 3.3 and 8.4 mm when compared with disease-free contralateral hips [154,157,158]. However, other authors have reported that resurfacing more accurately reproduced native horizontal femoral offset compared with total hip arthroplasty [154,158–160], which frequently produced a larger increase in this measurement. Most authors have reported postoperative mean femoral offset values within a few millimeters of the anatomic values, suggesting that any differences are clinically unimportant in properly selected patients. In addition, total hip resurfacing has been associated with potentially devastating adverse local tissue reactions similar to those seen with metal-on-metal stemmed total hip arthroplasty, and a better understanding of the pathogenesis and associated risk factors of these reactions is critical to ensuring reliable avoidance of these reactions and continued use of these bearings.

Summary

Modern metal-on-metal total hip resurfacing appears to provide excellent outcomes when performed by experienced surgeons in properly selected patients. This procedure may be especially suitable for young, active patients because it provides unique benefits in terms of preservation of femoral bone stock, stability of the prosthetic hip, and potentially more natural joint biomechanics. However, it is a distinct procedure that requires surgeons to learn new techniques from those used for standard total hip arthroplasty. Care must be taken to avoid intraoperative events associated with an increased risk of catastrophic early implant failure, such as notching of the femoral neck [137,161,162]. The risk of other potential complications associated with hip resurfacing, such as impingement and/or groin pain, can be reduced by ensuring appropriate component positioning, good coverage of the acetabular cup and meticulous osteophyte removal [163,164]. Surgeons should be aware that not all patients who are appropriate candidates for a standard total hip arthroplasty are similarly suited for a resurfacing. Patients with poor proximal femoral bone quality, including large head or neck cysts, osteopenia, extensive osteonecrosis and small femoral neck sizes, are at an increased risk for neck fracture and should be approached with caution [165].

Ceramic-on-ceramic hip arthroplasty

Origins, development & results

Ceramic-on-ceramic interfaces for hip arthroplasty were developed in an attempt to provide a more wear-resistant alternative to metal-on-polyethylene articulations, while avoiding the perceived issues of increased bearing friction and early component failure associated with early metal-on-metal components. These efforts were primarily centered in Western Europe, with a number of Austrian, French and German investigators developing and introducing aluminum oxide (alumina) ceramic bearings between 1971 and 1974 [166–169]. These devices consisted of a cemented or cementless metal femoral stem and modular ceramic femoral heads, articulating with a monolithic cementless (threaded or press fit) ceramic acetabular component [170,171]. An overview of selected reported survival rates for early and contemporary ceramic-on-ceramic bearings can be found in Table 3.

The clinical results of these early designs were less than satisfactory, with overall 10-year survivorship reported at between 75 and 84% by the innovator surgeons. Other authors have reported similar failure rates [172–175]. Many failures were the result of loosening of the monolithic ceramic acetabular component, which has been attributed to the large difference in the modulus of elasticity between the ceramic and bone, inadequate fixation and the lack of porosity for bone ingrowth [176]. For example, O'Leary *et al.* reported a 27% revision rate within 52 months of implantation with acetabular loosening in all cases [173]. These findings led to the introduction of composite acetabular components consisting of press-fit metal cups with a ceramic insert. Recently, Lewis *et al.* reported no acetabular loosening at a mean follow-up of 8 years in 30 patients treated with ceramic-on-ceramic total hip arthroplasty using a press-fit metal cup with ceramic insert [177]. It remains to be seen whether these promising results are maintained with other implant designs and at longer-term follow-up.

The early alumina-ceramic implants had also been reported to have a high incidence of component fracture. This material has a low fracture resistance necessitating the use of large femoral heads and thick-walled acetabular components; early attempts at using smaller heads (<32 mm) resulted in several reported femoral head failures [178]. In addition, early ceramic designs were plagued by poor design and material quality. In a clinical and biomechanical study of 35 retrieved alumina-on-alumina ceramic hip arthroplasty implants, Boutin *et al.* reported that component failure and/or excessive wear were associated with excessive material grain size, uneven grain distribution, presence of inclusion bodies, material porosity and a sphericity deviation greater than 1 µm [179]. The authors further reported that improved manufacturing quality control introduced in 1979 had addressed these issues, resulting in a near-absence of these modes of failure since that time. More recent advances in manufacturing technology have allowed the production of less brittle alumina ceramics, suitable for smaller-diameter femoral heads. Several authors have reported excellent outcomes of newer alumina-on-alumina total hip arthroplasty designs, with survival rates of between 94 and 97% at mean follow-up times of 7–10 years [180–186].

Table 3. Selected reported survival rates of historical and modern ceramic-on-ceramic bearings.

Study (year)	Number of hips (patients)	Mean follow-up time in months (range)	Survival (%)	Ref.
Early-generation alumina				
Petsatodis *et al.* (2010)	85 (78)	240	84†	[174]
Rousseau *et al.* (2004)	104 (81)	20 years	63	[263]
Lazzaro *et al.* (1999)	43 (38)	NR (7–13 years)	84	[264]
Huo *et al.* (1996)	27 (25)	73 (60–95)	85	[172]
Riska (1993)	290 (255)	64 (1–12 years)	92	[265]
Nizard *et al.* (1992)	187 (172)	120	83†	[205]
Winter *et al.* (1992)	100 (100)	NR (120–168)	75	[178]
Mahoney *et al.* (1990)	42 (34)	51 (27–66)	83	[175]
Sedel *et al.* (1990)	54 (NR)	NR (2–12 years)	96	[266]
O'Leary *et al.* (1988)	69 (62)	37 (24–52)	73	[173]
Late-generation alumina				
Lewis *et al.* (2010)	30 (30)	100 (58–121)	97	[177]
Bascarevic *et al.* (2009)	82 (78)	51 (34–63)	100	[267]
Greene *et al.* (2009)	103 (97)	50 (48–64)	100	[268]
Capello *et al.* (2008)	380 (275)	8 years (5 years to NR)	96†	[183]
Iwakiri *et al.* (2008)	82 (77)	80 (60–100)	91	[230]
Ha *et al.* (2007)	74 (64)	66 (60–72)	100	[269]
Sugano *et al.* (2007)	170 (143)	6 years (5–8 years)	99	[270]
Hasegawa *et al.* (2006)	35 (30)	70 (60–77)	83	[229]
Murphy *et al.* (2006)	194 (173)	50 (24–108)	96	[182]
Yoo *et al.* (2006)	72 (61)	69 (60–83)	100	[185]
D'Antonio *et al.* (2005)	222 (201)	62 (2–86)	97	[180]
Yoo *et al.* (2005)	93 (79)	68 (60–73)	100	[186]
Bizot *et al.* (2004)	71 (62)	108	94†	[181]
Garino (2000)	333 (NR)	22 (18–36)	99	[184]
Zirconia (note both ceramic-on-poly)				
Norton *et al.* (2002)	29 (26)	60	32†	[194]
Allain *et al.* (1999)	78 (61)	96	63†	[193]
Alumina composite				
Hamilton *et al.* (2010)	177 (NR)	31 (21–49)	98	[196]
Lombardi *et al.* (2010)‡	65 (NR)	73 (26–108)	95	[197]

†Survivorship at noted follow-up time.
‡Study of composite femoral head on pure alumina liner.
NR: Not reported.

Zirconia ceramic femoral heads were introduced between the late 1980s and early 1990s in an attempt to increase the fracture resistance of these implants, allowing the use of smaller, 22- and 26-mm diameter heads. While pure zirconia is an unstable material exhibiting three distinct crystalline phases – monoclinic, tetragonal and cubic [56] – the introduction of yttrium oxide during manufacturing was meant to stabilize zirconia in the most stable, tetragonal phase. However, several authors reported early fractures and evidence of phase instability *in vivo* with this material [187–192]. Survivorship of between 32 and 63% at follow-up times of 5 and 8 years, respectively, have been reported with these implants, and they have been largely abandoned [193,194].

Most recently, a composite yttrium-stabilized ceramic composed of aluminum oxide, zirconia and chromium has been introduced for clinical use. It is hoped that this material will improve on the good clinical outcomes of contemporary alumina-on-alumina bearings by further increasing fracture resistance and reducing wear. In an *in vivo* study of 28-mm ceramic heads, Streicher *et al.* found a 91% reduction in volumetric wear with composite material compared with alumina bearings [195]. The reported short-term results with this new compound range from 95 to 98% at follow-up times of 2–9 years [196,197]. There is additional ongoing research on new ceramic materials for total hip arthroplasty, with recent *in vitro* studies suggesting that silicon nitride bearings might provide fracture toughness approaching traditional metal implants while retaining the low wear characteristics of current ceramic bearings [198–200].

Potential advantages of ceramic bearings

The principal potential advantages of ceramic bearing surfaces include very low wear rates and minimal adverse reactions to wear debris. *In vivo* testing of modern alumina-on-alumina bearings has demonstrated steady-state volumetric wear rates of between 0.004 and 0.05 mm^3 per million cycles [201], which are approximately three orders of magnitude lower than the expected wear rates for traditional metal-on-polyethylene articulations. These findings have been confirmed in retrieval analysis studies reported by Dorlot *et al.* and Prudhommeaux *et al.*, who reported mean annual wear rates of between 0.025 and 0.05 μm/year [202,203]. This represents an approximately 100-fold decrease in linear wear compared with metal-on-metal articulations, and between a 2000 to 10,000 decrease compared with metal-on-polyethylene implants. Hamadouche *et al.* reported no measurable wear on serial plain radiographs of 51 ceramic-on-ceramic total hip arthroplasties at follow-up times between 18 and 20 years [204]. These exceptionally low wear rates are believed to result from a combination of the superior hardness of the ceramics used and the effective lubrication associated with the material's hydrophilic properties, as well as the strict manufacturing tolerances.

Ceramic-on-ceramic bearings have also been shown to have a high biocompatibility, with markedly lower incidences of wear-related osteolysis when compared with polyethylene bearings. There have been some reports of osteolysis following ceramic-on-ceramic total hip arthroplasty, but most were either with early-generation materials or attributed to technical errors at the time of implantation [176,181,205–209]. Hatton *et al.* reported that alumina-ceramic wear particles were capable of inducing osteolytic cytokine production in donor mononuclear cells, but the minimum required concentration was sufficiently large that it was unlikely to be reached even in abnormal wear conditions with modern ceramic implants [210]. Concordant with these findings, a number of authors have reported no evidence of femoral osteolysis when evaluating series of between 93 and 241 contemporary ceramic-on-ceramic total hip arthroplasties at mean follow-up times ranging from 6.5 to 11 years [182,211,212].

Ceramic wear particles appear to have little effect on cellular function, even at concentrations substantially above those seen in cases of abnormal wear. Germain *et al.* reported that the viability of histiocytes and fibroblasts was decreased by 97 and 67%, respectively, compared with controls when cultured with 50 μm^3 per cell of cobalt chromium wear particles [213]. By contrast, no effect on viability was found when cells were cultured with the same concentration of alumina-ceramic wear particles. Histological analysis of periprosthetic tissues in two retrieval studies of aseptically-loosened early-generation ceramic prostheses with monolithic acetabular components revealed areas of macrophage infiltration with evidence of intracellular ceramic wear debris and, in some specimens, the presence of neutrophils and lymphocytes [209,214]. However, these reports have been limited to a single implant design with a high reported failure rate, and to the best of the authors' knowledge, there have been no reports of local immune-mediated adverse effects with ceramic bearing couples.

Potential disadvantages of ceramic bearings

The principal potential disadvantages of ceramic-on-ceramic bearings are the potential for implant fracture, chipping and squeaking. The increased brittleness of ceramic implants compared with metal bearings was well recognized even with first-generation implants. Fracture of ceramic components is a particularly devastating complication because of the large number of fragments typically dispersed into the joint, and retained debris can result in rapid wear of newly implanted components following revision surgery even with meticulous debridement and irrigation [215–217]. Unacceptably high fracture rates were reported with several early ceramic-on-ceramic implants, ranging from 1.3 to as high as 13.4% [205,218–220]. Some of these failures were attributed to poor tolerances in the design of the taper fit between the metal femoral component and ceramic head [221]. Analysis of early ceramic materials and retrieved failed components led to several modifications in both the raw materials used in the formation of the ceramic components, as well as in the manufacturing process [222]. Improved raw materials were adopted that had a finer grain size and lower level of impurities. The ceramic firing process was changed to form the implants under high pressure but lower temperature, which reduced the ceramic grain size, while increasing the material density. These two modifications resulted in the production of implants with improved mechanical strength. Also, thorough quality control processes were implemented, including mechanical stress testing of each implant at a load that is above the maximum expected physiologic load, but below the estimated failure point. As a result of these changes, contemporary alumina-ceramic femoral heads have been reported to have a fracture incidence of 0.004% based on tracking data from one of the largest manufacturers of these implants [222]. The improved structural stability of recently introduced alumina–zirconia–chromium composite implants suggests that the fracture rate of ceramic hip components may be further reduced [223]. However, *in vivo* fractures have been reported and it remains to be seen whether a reduced failure rate will materialize through large-scale implant tracking [197].

Ceramic-on-ceramic bearings are also susceptible to component chipping, either at the time of component implantation or postoperatively. These deformities in the bearing surfaces can potentially result in rapidly accelerated wear. Intraoperative chipping or fracture does not appear to adversely affect postoperative outcomes providing it is identified by the surgeon and the failed components are removed and replaced [180,196]. However, a number of investigators have reported postoperative chipping of the acetabular rim or femoral head [196,224–228], which is believed to occur as a result of point-loading of the component at the time of dislocation of the hip, closed reduction, subluxation of the prosthetic head or impingement of the femoral neck on the liner. Some manufacturers introduced a composite acetabular liner consisting of a recessed ceramic surface inside a polyethylene liner to prevent contact between the femoral neck and ceramic liner, and potentially also improve longevity by reducing the stiffness of the bearing couple. However, this design was found to have a high rate of liner fracture and/or dissociation [229,230]. Other manufacturers have introduced modular acetabular components consisting of a ceramic liner recessed into a titanium sleeve to prevent impingement-related chipping [231]. While these designs appear to successfully reduce chipping, several authors have reported a high incidence of liner mal-seating with these implants, ranging from 7.2 to 16.8% [232–234]. However, the clinical relevance of these findings remain unknown, and in some cases the liners have been found to seat properly at subsequent radiographic evaluation [232]. Nevertheless, achieving optimal component positioning and joint stability intraoperatively is critical to minimize the possibility of dislocation or impingement and subsequent component chipping. In addition, because of the relatively large material thicknesses needed to reduce the risk of component chipping, as well as the need to nest the ceramic acetabular liner in a metal shell, the implant choices and largest femoral head size that can be used with a given acetabular outer diameter are substantially reduced when compared with metal-on-metal designs, potentially adversely affecting joint stability and gait biomechanics.

A recently reported potential disadvantage of ceramic-on-ceramic bearings is the reported occurrence of audible squeaking. The incidence of this complication is variable, ranging from 0.5 to 21% [235–239]. The etiology of this phenomenon remains elusive. A number of authors have variously reported that it is associated with third body wear from ceramic or particles [240], stripe wear [241], component malpositioning [239] and impingement with resultant edge loading [242]. Chevillotte *et al.* postulated that the common pathway for squeaking is decreased bearing lubrication [243], which may result from any of the other proposed etiologies. Certain implant designs may predispose to a higher incidence of squeaking. In a review of 1139 primary ceramic-on-ceramic total hip arthroplasties implanted at a single center, Ecker *et al.* reporting a significantly higher incidence of squeaking in patients who received either of two recessed acetabular liners, compared with those treated with a flush-mounted liner (7.6 vs 3.1% [p = 0.002] vs 0.6% [p = 0.04], respectively) [244]. The authors concluded that the squeaking was the result of contamination of the bearing with metal particles generated by impingement of the femoral neck on the acetabular rim. The clinical relevance of squeaking hips remains unknown. The large majority of patients have well-functioning hips and report high satisfaction with the results of the arthroplasty procedure despite the noise [237], and anecdotal reports have been made of spontaneous resolution of squeaking [245]. Nevertheless, it is clear that some patients are bothered by having a noisy hip even if it is functioning well. As the understanding of this phenomenon continues to improve, it is likely that modifications in implant design and surgical technique will reduce the overall incidence of this phenomenon to well below 1%, as is already reported by several authors.

Summary

Many early ceramic-on-ceramic implant designs demonstrated suboptimal survival rates, with chipping or fracture of the articulating surfaces, and early loosening of acetabular components. Substantial improvements in raw materials, component designs and manufacturing techniques have been made over successive generations of implants, and modern ceramic-on-ceramic hip arthroplasty has demonstrated excellent survival rates, extremely low wear rates and an exceptionally low incidence of catastrophic failure. Some concerns remain regarding adverse events, such as component squeaking, that rarely appear to adversely affect the mechanical function of the implant, but can be very bothersome to patients. New ceramic materials continue to be introduced that promise to further improve the performance of these bearings, and investigations are ongoing concerning potential associations between implant design factors and the incidence of squeaking. Some surgeons have advocated the use of ceramic femoral heads articulating with highly cross-linked acetabular components, postulating that this bearing couple will provide reduced wear compared with metal-on-polyethylene while reducing the incidence of complications, such as ceramic failure or squeaking. Hamilton *et al.* recently reported similar survivorship and complication rates in a prospective randomized comparison of ceramic-on-ceramic and ceramic-on-cross-linked polyethylene total hip arthroplasty at a mean follow-up of 31 months (range: 21–49 months) [196]. However, longer follow-up is necessary to assess any differences in terms of wear rates and long-term survival.

Ceramic-on-metal

Origins, development & results

Some clinical investigation is currently taking place into the outcomes with ceramic-on-metal articulations, although little is known regarding this alternative bearing couple secondary to its recent introduction into the orthopedic community. In 2001, the results of a hip simulator study revealed a 100-fold reduction in volumetric wear with ceramic-on-metal bearings when compared with metal-on-metal articulations over 5 million cycles [246]. Since then, the results other *in vitro* wear simulator studies have been reported, confirming these findings [247,248]. The lower wear has been attributed to a reduction in corrosive wear, improved lubrication, smoother surfaces and the differential hardness between metal and ceramic, reducing adhesive wear [248,249].

Potential advantages & disadvantages

A potential advantage of using this type of articulation is a reduction in metal ion production compared with traditional metal-on-metal bearing surfaces. Prospective randomized clinical trials are currently being conducted in Europe and the USA to evaluate this interface, and early reports have revealed lower metal ion levels in the ceramic-on-metal bearing surfaces as compared with the metal-on-metal articulations. Williams *et al.* reported that the mean increases in cobalt and chromium ion levels in 31 hips 6 months following implantation were 2 and 4 µg/l, respectively, in patients with ceramic-on-metal hips, as compared with 6 and 10 µg/l, respectively, in those with metal-on-metal hips [248]. At 12-month follow-up, Issac *et al.* reported a lower mean increase in whole blood ion levels in patients with ceramic-on-metal articulations (0.02 and 0.08 µg/l for cobalt and chromium, respectively) compared with metal-on-metal bearings (0.32 and 0.48 µg/l), with the difference in chromium levels reaching significance (p = 0.02) [250].

In addition, because the material properties of cobalt–chromium allow the use of a substantially thinner acetabular component as compared with ceramic liner, larger femoral heads can be used in ceramic-on-metal articulations, lowering the theoretical risk of femoral head dislocation and fracture.

While there is promising early data on metal-on-ceramic bearing surfaces, there is insufficient data available to assess the potential disadvantages of this interface, and more clinical data over longer follow-up periods is necessary before this bearing surface becomes incorporated in modern total hip arthroplasty.

Expert commentary & five-year view

This article was written as an overview of the field of hard-on-hard bearings and their dramatic evolution since they were first used over a half a century ago. However, there are certainly limitations with this article, because the presently used devices have mostly mid-term follow-up with very few level I studies to compare results and assess the advantages and disadvantages of different interfaces. Early uses of each of the described interfaces were marked by high failure rates and skepticism within the orthopedic community concerning their suitability for clinical use. However, as analysis of the failures led to improvements in component designs, materials, manufacturing and surgical techniques, success rates with both metal-on-metal and ceramic-on-ceramic articulations improved. Currently, excellent survival rates have been reported by a number of investigators with each of these couples, with decreased incidences of the complications associated with conventional metal-on-polyetheylene bearings, namely increased wear and osteolysis. Further studies of various unresolved issues, needed to more clearly understand the advantages and disadvantages of these interfaces, are underway, and the findings are expected to affect the relatively popularity of the interfaces discussed in this report. Despite an almost 50-year history of the use of metal-on-metal bearings, substantial concern has been raised in the orthopedic community concerning adverse local tissue reactions with the use of these articulations over the past few years. Although the true incidence of symptomatic reactions appears to be low, it is critical that the pathogenesis of these reactions is more clearly elucidated and the risk factors and incidence in different patient populations more accurately described. Newer-generation ceramics have shown excellent wear resistance and, in contrast with early materials, low fracture rates. It is expected that the use of ceramic femoral heads will continue to increase, although it remains to be seen whether ceramic-on-ceramic interfaces will gain in popularity as compared with ceramic-on-highly cross-linked polyethylene. Adverse events from any of the described hard-on-hard bearings can be minimized by appropriate component positioning. However, the higher cost of these bearings relative to metal-on-polyethylene is a remaining concern that may limit their increased adoption, especially in the current environment of greater healthcare cost awareness and a predicted marked increase in the demand for joint arthroplasty over the coming decades.

Nevertheless, as bearing designs continue to improve with new and modified materials and manufacturing techniques, and consistently good longer-term clinical results with newer-generation bearings are reported, it is likely that the use of hard-on-hard bearings will continue to increase over the coming 5 years, especially in young and active patients.

Financial & competing interests disclosure

Michael A Mont is a consultant for Stryker Orthopaedics and Wright Medical, receives royalties from Stryker and receives research or institutional support from Stryker, Wright Medical, the National Institutes of Health (NIAMS and NICHD) and Tissue Gene. Thomas P Schmalzried is a board member of the Orthopaedic Research and Education Foundation, is a member of the editorial board for Orthopedics Today, receives royalties from DePuy and Stryker, is a consultant for Stryker, receives research or institutional support from DePuy and Stryker, and holds stock or stock options in Johnson and Johnson, Smith and Nephew, Stryker and Zimmer. Michael G Zywiel serves on the editorial board of Expert Review of Medical Devices. The authors have no other relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript apart from those disclosed.

No writing assistance was utilized in the production of this manuscript.

Key issues

- Hard-on-hard bearings for total hip arthroplasty have been in use almost as long as metal-on-polyethylene bearings.
- Metal-on-metal total hip arthroplasty allows for the use of near-anatomic-sized femoral heads when combined with monoblock acetabular components. This may improve lubrication and decrease wear, as well as improve joint stability and reduce the incidence of dislocations.
- Recent concerns have been raised concerning adverse local tissue reactions with metal-on-metal articulations. However, the true incidence and pathogenesis of these reactions remains unknown, and the great majority of patients who have received these bearings remain asymptomatic.
- Contemporary metal-on-metal hip resurfacing has been in clinical use for approximately 10 years, and excellent survival rates have been reported when performed by innovator surgeons. The overall reported results have been more variable, but several studies have suggested that appropriate hands-on training and sufficient clinical volume are critical to achieve reproducibly good results.
- Substantial innovations have been made over the past 40 years in the manufacture of ceramics for total hip arthroplasty. A fracture rate of 0.004% over approximately 500,000 femoral heads has been reported with one of the newer-generation ceramics.
- A notable incidence of squeaking has been reported with ceramic-on-ceramic articulations by some investigators. However, no mechanical complications have been reported with this phenomenon, and it appears that it is limited to a specific implant design.

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