

Alumina-on-Polyethylene Bearing Surfaces in Total Hip Arthroplasty

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Abstract: The long-term durability of polyethylene lining total hip arthroplasty (THA) mainly depends on periprosthetic osteolysis due to wear particles, especially in young active patients. In hip simulator study, reports revealed significant wear reduction of the alumina ceramic-on-polyethylene articulation of THA compared with metal-on-polyethylene bearing surfaces. However, medium to long-term clinical studies of THA using the alumina ceramic-on-polyethylene are few and the reported wear rate of this articulation is variable. We reviewed the advantages and disadvantages of ceramic-on-polyethylene articulation in THA, hip simulator study and retrieval study for polyethylene wear, *in vivo* clinical results of THA using alumina ceramic-on-polyethylene bearing surfaces in the literature, and new trial alumina ceramic-on-highly cross linked polyethylene bearing surfaces.

Keywords: Arthroplasty, polyethylene, alumina.

1. INTRODUCTION

Alumina ceramic was introduced as a bearing surface in the 1971 as an alternative to the metal on-polyethylene couplings. Since then, alumina ceramic has been used in THA successfully for more than 35 years. Alumina 1970s (first generation) had a low density, a very coarse microstructure, sintered in air, and was not in compliance with specifications. Alumina 1980s (second generation) had a reduced microstructure grain size, had a laser marking, and sintered in air. Alumina 1990s (third generation, forte) had a improved mechanical strength, more reduced microstructure grain size, laser marking, proof testing of 100%, and manufactured by using hot isostatic pressing. In 2000s (fourth generation, delta), a new alumina matrix composite material with improved material properties was developed. The advantages of using alumina ceramic as a bearing surface in THA are related to its hardness, wettability, fluid film lubrication, inertness, high level of oxidation of alumina ceramic which provide resistance to scratches, and high biocompatibility [1, 2]. These characteristics seem to make less polyethylene wear when alumina ceramic head articulates with polyethylene than metal head. *In vitro* hip simulator studies of alumina ceramic-on-polyethylene articulations, the wear rate of polyethylene with the alumina ceramic head was lower than that of polyethylene with metal head. Also, at equivalent particle volumes the clinically relevant alumina particles showed less toxic than cobalt-chrome particles *in vitro* [2]. The disadvantages of alumina ceramic-on-polyethylene bearing surfaces involves the risk of alumina head fracture and the resultant difficult revision surgery [3], and metal transfer which can increase surface roughness and third body wear leading to increased polyethylene wear [4].

2. KINDS OF CERAMIC FEMORAL HEADS

Alumina (Al_2O_3) and zirconia (ZrO_2) ceramic femoral heads have been widely used as more scratch-resistant bearing surfaces against PE. Alumina and zirconia heads both have high hardness and strength, which make them more difficult to scratches, and this can reduce abrasive wear. The wettability of ceramic material is another important property. Ceramics are more hydrophilic and have improved lubrication and lower friction. The fracture toughness of zirconia is reported as nearly twice that of alumina and it had higher strength, lower variability than alumina. These properties of zirconia allowed smaller heads and more neck length than alumina without increased risk of fracture. However, zirconia femoral heads have not performed clinically as well as alumina heads [5, 6]. Phase transformation that can occur over a ten-year period, grain pullout, roughening, inferior wear properties, and a manufacturing-related fracture problem have resulted in the withdrawal of zirconia femoral heads in the market in 2002. Alumina ceramics showed high survivorship and low bearing wear, but concern of ceramic fracture and the resultant difficult revision surgery still persists. A new alumina matrix composite material with improved material properties was developed to address these concerns and early results showed hopeful in both ceramic-on-ceramic and ceramic-on-polyethylene articulation [7].

3. HIP SIMULATOR STUDIES FOR WEAR OF ALUMINA-ON-POLYETHYLENE ARTICULATION

There are a few hip simulator studies of alumina-on-polyethylene articulations. The wear rate of polyethylene with the alumina head was lower than that of polyethylene with metal head. Saikko *et al.* reported the mean wear rate of cups against alumina heads was usually lower than against metallic heads in hip simulator study with saline as a lubricant, raising doubt about the clinical applicability [8]. Also, Clarke *et al.* reported in bovine serum based hip simulator study, alumina ceramic-on-polyethylene hip

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replacement systems offered on average a 50% wear reduction from metal-on-polyethylene systems [9].

4. A RETRIEVAL STUDIES FOR WEAR OF ALUMINA-ON-POLYETHYLENE ARTICULATION

There are contradictory results for wear rate in a retrieval study. Bragdon *et al.* suggested that alumina ceramic-on-polyethylene wear rates are not substantially different from metal-on-polyethylene [10]. However, Kusaba and Kuroki found lower polyethylene wear for alumina compared with CoCr 32-mm heads [11].

5. CLINICAL STUDIES FOR WEAR OF ALUMINA-ON-POLYETHYLENE ARTICULATION

In clinical practice, there also have been confusing data about wear of alumina-on-polyethylene articulation even though mostly encouraging results. Urban *et al.* reported a head penetration rate of 0.034mm per year with a 32mm alumina head-on-gamma irradiated in air polyethylene articulation at 17 to 21 year follow-up [12]. Hernigou and Bahrami a head penetration rate of 0.071mm per year with a 32mm head alumina-on-polyethylene articulation at 10.8 year follow-up [13]. We previously reported a head penetration rate of 0.07mm per year with a 28mm head alumina-on-polyethylene articulation after a mean 9 year and 7 year follow-up measured using Livermore method, and Dorr and Wan method respectively [14, 15].

There are studies comparing the wear of ceramic and metallic heads. Zichner and Willert compared the radiological wear characteristics of metal and alumina ceramic femoral head articulating with polyethylene [16]. Using metallic balls using Proxasul-2, 64% had a wear rate of less than 0.2mm; of those using Proxasul-10, 77% had lower rates than 0.2mm. In patients where alumina balls were implanted, the displacement rate was below 0.2mm per year in 95%. Clarke and Gustafson indicated that alumina ceramic-on-polyethylene hip replacement systems offered on average a 50% wear reduction from metal-on-polyethylene system in laboratory and clinical data [9]. Oonishi and coworkers reported a 0.1mm per year rate head penetration rate with alumina ceramic femoral heads compared with a 0.25mm per year rate with stainless steel femoral heads [5]. Schuller and Marti reported a 0.03mm per year rate head penetration rate with alumina ceramic femoral heads compared with a 0.10mm per year rate with CoCr femoral heads after 9 to 11 year follow-up [17]. But variables such as age, weight, acetabular and femoral components, size of the head, manufacturer of the head, and surgical technique were not addressed in these studies.

Later, the performance of polyethylene liners articulating with alumina ceramic heads was compared with that of polyethylene liners articulating with cobalt-chrome heads in two groups of patients that were matched on age, gender, weight, acetabular and femoral components, size of the head, manufacturer of the head and surgical technique. Sychterz *et al.* compared the radiological wear characteristics of 81 alumina ceramic femoral heads with a well-matched group of 43 cobalt-chrome femoral heads [18]. At a mean of seven years the true rate of wear of the ceramic group was slightly greater (0.09mm/year) than that of the cobalt-chrome group (0.07mm/year). Despite the numerous theoretical advantages

of alumina ceramic over cobalt-chrome femoral heads, the wear performance *in vivo* of these components was similar.

Some reports showed discouraging results. Japanese authors have investigated the long-term results of cemented THA with Bioceram prostheses (Kyosera, Kyoto, Japan) and reported higher wear rate of polyethylene. The mean linear wear rates of 0.10mm/year at 13 years and 0.15mm/year at 13.8 years of follow-up respectively [19, 20].

Various wear rate of alumina-on-polyethylene bearing THA are listed at Table 1 [5, 12-16, 18, 20-30].

There are studies comparing the wear of alumina-on-alumina articulation compared with alumina ceramic-on-polyethylene recently. Hernigou *et al.* reported a head penetration rate of 0.07mm per year alumina ceramic head-on-polyethylene articulation and a head penetration rate of 13um per year alumina-on-alumina articulation on 28 bilateral arthroplasties in same patients at minimum 20 year follow-up [31]. Lewis *et al.* reported a wear rate of 0.11mm per year with a 28mm alumina ceramic head-on-polyethylene articulation and a head penetration rate of 0.02 um per year alumina-on-alumina articulation measured using the method of Dorr and Wan up to 10 year follow-up in a prospective randomized trial [29].

6. CONCERN OF CERAMIC COMPLICATIONS

There is possibility of a fracture of a ceramic head because ceramics are brittle materials [32-34]. Low fracture toughness and linear elastic behavior demonstrated by ceramic make it prone to breakage under stress. The risk of alumina head fracture is low but considerable when it occurs. Reoperation is necessary, and the outcome of the revision arthroplasty for ceramic femoral head fracture will be compromised because of retained ceramic fragments that have been shown to increase wear, to increase the development of osteolysis, and to increase the need for another revision surgery. Heavy patients and reconstructions with longer neck lengths (less contact area along taper junction) and/or high offsets appear to be at increased risk. Theoretically, improvements in Morse taper design and manufacturing can minimize or eliminate this problem.

Clinically the risk of ceramic head fracture seems to be higher when articulating with rigid bearing than polyethylene one. Willmann reported on a fracture rate of 0.02% in 1.5 million heads since 1974 [35]. In a later review of the literature, he reported on a failure rate of ceramics up to 13.4 % manufactured before 1990 and a failure rate of 0.004% to 0.015% for ceramics manufactured after 1990 [36]. Especially for the BioloX femoral head, Willmann saw a fracture rate of 0.026% for first generation alumina (1970s), 0.014% for second generation alumina (1980s), and 0.004% for third generation alumina femoral heads (BioloX forte) manufactured after 1994 (1990s). Fritsch *et al.* analyzed over a period from 1974 to 1998, 4,341 alumina ceramic heads articulating with 2,693 alumina ceramic and 1,464 polyethylene cups [37]. They reported only one fracture of a alumina ceramic head in a alumina ceramic-on-polyethylene articulation and seven fractures in alumina-on-alumina articulation whereas four fractures were related to direct trauma, two fractures were related to recurrent neck impingement and one was due to material fatigue. Heisel reported on two traumatic fractures of alumina ceramic

Table 1. Studies of Wear Rates of Alumina-on-Polyethylene Bearing Total Hip Arthroplasty

Study	No. of Hips	Follow-Up Duration (Year)	Acetabular Bearing	Diameter (mm)	Linear Wear Rates (mm/Year)	Range Linear Wear Rates	Wear Measurement
Zichner <i>et al.</i> [16]		5	UHMWPE			0.1-0.2	Buchhorn
Sugano <i>et al.</i> [29]	57	11.1	UHMWPE	28	0.10	0-0.31	Computerized
Wroblewski <i>et al.</i> [21]	19	6.4	XLP	22.225	0.06	0.024-0.32	Collins
Livingston <i>et al.</i> [22]	7	14-16	Hylamer	28	0.33		Livermoore
Sychterz <i>et al.</i> [23]	9	10-19	UHMWPE	32	0.16		Computerized
Sychterz <i>et al.</i> [18]	81	7	UHMWPE	32	0.09		Computerized
Oonish <i>et al.</i> [5]	12		100Mrad PE	28	0.05	SD 0.03	Livermoore
	111		UHMWPE	28	0.1	SD 0.007	Livermoore
Hasegawa <i>et al.</i> [24]	44	13	UHMWPE	28	0.1		Livermoore
Haraguchi <i>et al.</i> [20]	101	14	UHMWPE	28	0.15	0.04-0.34	Computerized (Sugano)
Urban <i>et al.</i> [12]	18	18.2	UHMWPE	32	0.034	0.00016-0.077	Livermoore
Tanaka <i>et al.</i> [30]	67	13.6	UHMWPE	28		0.036-0.365	Computerized
	41	10.8	UHMWPE	26		0.005-0.199	(Sychterz)
	48	9.2	UHMWPE	22		0.007-0.342	
Hernigou and Bahrami [13]	56	10.8	UHMWPE	32	0.071	0.041-0.101	Magnifier (Devane)
Kim <i>et al.</i> [15]	101	9.2	UHMWPE	28	0.07	0.01-0.27	Livermoore
Kim <i>et al.</i> [14]	67	7	UHMWPE	28	0.07	0.01-0.23	Dorr and Wan
Wroblewski <i>et al.</i> [25]	11	17	XLP	22.225	0.019	0-0.026	Collins
Liang <i>et al.</i> [26]	46	6.7	UHMWPE	22	0.078	0.02-0.27	Computerized (Sychterz)
Kim <i>et al.</i> [27]	30	11.3	UHMWPE	28	0.1	0.09-0.12	Computerized
Lewis <i>et al.</i> [28]	26	8.1	UHMWPE	28	0.11		Dorr and Wan
Kim <i>et al.</i> [44]	100	5.6	HXLPE	28	0.06	0-0.08	Computerized

heads articulating with polyethylene in 2356 alumina ceramic hip endoprotheses [38]. Reviewing the literatures, they came to the conclusion that a fracture of the alumina ceramic head may be prevented by using a alumina ceramic-on-polyethylene combination. The other concern of alumina femoral head is metal transfer which can increase surface roughness and third body wear leading to increased polyethylene wear [4].

Hasegawa *et al.* reported that the retrieved alumina heads (28mm Bioceram) showed smooth surfaces without scratches, but there was debris stuck to the gaps on the surfaces [19]. The authors attributed these results to uncontrolled factors, such as third-body wear and levels of activity. This result is contrary to the report of Wang and Essner [39]. They found that ceramic heads were effective in reducing polyethylene wear because of the inability of third-body particles to adhere to their surfaces rather than due to their resistance to scratching.

Squeaking is another problem of alumina-on-alumina bearing surface. This phenomenon had not been reported in alumina-on-polyethylene articulation and is unique in ceramic-on-ceramic articulation.

7. WEAR FOR ALUMINA-ON-HIGHLY CROSS-LINKED POLYETHYLENE BEARING SURFACE

The successful long-term clinical experience with ultra-high molecular weight polyethylene as a bearing surface has prompted the development of more wear-resistant highly cross-linked polyethylene [26]. The principle is to enhance chain cross-linkage between crystals by radiation and avoid free radical oxidation by secondary heat treatment. This change in structure should significantly improve wear resistance and reduce polyethylene wear debris release and it have shown excellent medium-term clinical results [26, 40]. The manufacturing processes of the currently available products differ in dose and type of irradiation (gamma radiation or electron beam), thermal stabilization (remelting or annealing), machining, and final sterilization. This treatment significantly improves wear, and alters the mechanical properties of polyethylene, proportionally to the radiation dose. Even so, *in vitro* hip simulator studies show a very low wear rate unaffected by the use of large head diameters [41].

Wroblewski *et al.* confirmed hip simulator results for the wear characteristics, that alumina ceramic femoral heads penetrate the highly chemically cross-linked polyethylene cups at only about half the rate of otherwise comparable

metal heads [21]. Subsequently, he reported a head penetration rate of 0.019mm per year with a 22.225mm alumina ceramic head-on-chemically cross-linked polyethylene articulation at 17 year follow-up [26]. Oonishi *et al.* reported a head penetration rate of 0.05mm per year with a 28mm alumina ceramic head-on-100Mrad irradiated cross-linked polyethylene articulation at 14-16 year follow-up [26]. There is only one clinical trial using alumina ceramic-on-currently available highly cross-linked polyethylene bearing surface in the literature. Kim *et al.* reported the mean annual penetration of 0.06mm in cementless THA with 28mm alumina ceramic (forte)-on-highly cross-linked polyethylene (Marathon, Depuy, Warsaw, Indiana, USA) bearing surface after 5.6 years follow-up in the 100 patients younger than 50 years of age. Callaghan continues to use alumina ceramic-on-highly cross-linked polyethylene bearing surfaces in the patients at higher risk for wear in THA [42].

These new polyethylenes, on the other hand, show reduced resistance to cracking (lower plasticity). Holley *et al.* studied an impingement model on a hip simulator and found greater wear under these condition [43]. Overall, there is less tolerance than with conventional polyethylene, and the disadvantages resemble those of hard-on-hard couples. But most reports support that clinical findings confirm the good trend.

8. CONCLUSION

Although there are different wear rate in hip simulator studies and retrieval studies about alumina ceramic-on-polyethylene articulation, the clinical wear performances of these articulations in THA showed significant reduction of polyethylene wear compared with meta-on-polyethylene articulation. Mostly, wear rate of alumina ceramic-on-polyethylene articulation showed less than “so called osteolysis threshold” of 0.10mm per year. Also, incidence of alumina ceramic head fracture was rare compared with ceramic-on-ceramic bearing surfaces. Squeaking in alumina-on-alumina bearing surface had not been reported in alumina ceramic-on-polyethylene articulation.

Competition between various articulations in order to reduce wear and to improve the longevity of THA will be continued through next decades. In that, alumina ceramic-on-polyethylene including recently developed highly cross-linked polyethylene articulation would be remained as a good option for THA especially young and active patients. Further manufacturing and material development, improvements in the processing of ceramic as well as advances in engineering of head-neck articulations and liner design will lead to more favorable clinical results and decrease in the incidence of ceramic fracture and dislocation. In future, it is necessary to perform prospective randomized comparative studies to compare various bearing surfaces in patients matched in age, sex, diagnosis, body mass index, kinds of polyethylene and ceramic head according to manufactures, head diameter, follow-up period, and measuring method for wear.

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